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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

Edited by

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

HENRY G. GALE
Ryerson Physical Laboratory of the University of Chicago

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REPULSIVE FORCES IN SOLAR PROMINENCES

BY N. T. BOBROVNIKOFF

ABSTRACT

The repulsive force $1-\mu$ has been computed in thirteen cases for Ca^+ prominences and in eight cases for $H\alpha$ prominences. The mean value for Ca^+ is $1-\mu=1{\cdot}133\pm0.014$, and for H, $1-\mu=1.387\pm0.055$, times the gravitational attraction of the sun.

The repulsive force for both Ca^+ and H increases with the mean distance of the prominence from the solar surface. This has been interpreted as due to the increase in the velocity and the corresponding Doppler effect, according to Milne's theory. From the curve correlating $1-\mu$ with the mean velocity v_0 it is found that $1-\mu$ for $v_0=200$ km/sec. should equal 1.9 times $1-\mu$ for $v_0=0$. Using the Doppler shift 2.6 A corresponding to $v_0=200$ km/sec., it is found from Unsöld's contour of the K line of Ca^+ that $1-\mu$ at this velocity should be equal to 1.9. That is in exact agreement with observation. Minnaert's determination of the contour of the K line gives $1-\mu=2.8$.

It is shown that the value $1-\mu=1.39$ derived by Woltjer for Ca^+ is probably too large. The error may be explained by the uncertainty of the data involved.

Even those prominences whose motion can be represented by smooth lines often change their $1-\mu$ and v_0. This is in striking analogy with the behavior of CO^+ in comets' tails.

INTRODUCTION

The motion of matter in solar prominences has been a subject of numerous investigations of a theoretical character. Various attempts have been made to compute the repulsive force of solar radiation on the Ca^+ atom. They usually involve some assumptions of a physical character with the corresponding uncertainty of the results.

As the motion of prominences is under a repulsive force emanating from the sun, the methods used in the physical theory of comets can be applied to this case. It is possible to compute the repulsive force of the sun without making the assumption that it is due to light-pressure.

The motion of a particle under the influence of a central force, acting according to the law of Newton, is defined by the following familiar equations:

$$\left.\begin{aligned} r^2\frac{d\theta}{dt}&=h\,,\\ \frac{d^2r}{dt^2}&=\frac{f}{r^2}+\frac{h^2}{r^3}\,,\end{aligned}\right\} \tag{1}$$

where r is the radius vector, θ is the angle between r and a certain fixed direction, h is the area constant, and f is the force.

From (1) we obtain

$$f=r^2\frac{d^2r}{dt^2}-r^3\left(\frac{d\theta}{dt}\right)^2\,. \tag{2}$$

In the case of prominences angle θ does not change much, so that the second term in (2) may be neglected. At any rate, by doing so we shall obtain the maximum value of the force acting on the prominence. The problem is therefore reduced to finding the second derivative of the radius vector at a certain time t_0. Denoting $(dr/dt)_{t=t_0}$ by r_0', $(d^2r/dt^2)_{t=t_0}$ by r_0'', etc., we have

$$r=r_0+(t-t_0)r_0'+(t-t_0)^2\frac{r_0''}{2}+(t-t_0)^3\frac{r_0'''}{3}+\cdots\cdot\,. \tag{3}$$

Differentiating the second of equation (1) and neglecting the term with h, we have

$$r_0'''=-\frac{2f}{r_0^3}\,r_0'=-\frac{2r_0'r_0''}{r_0}\,, \tag{4}$$

so that formula (3) becomes

$$r=r_0+\left(t-\frac{r_0''}{3r_0}\,t^3\right)r_0'+t^2\frac{r_0''}{2}+\cdots\cdot\,, \tag{5}$$

if we count the time from the moment t_0.

In the case of the solar prominences the term $(r_0''/3r_0)t^3$ is small

[1] The method used here is substantially that of A. J. Orlow, *Publ. der K. U. Sternwarte zu Jurjew*, **21**, Heft 3, 1910.

and can generally be neglected. In several cases r_0 and r_0'' were obtained from a preliminary solution of equation

$$r=r_0+tr_0'+t^2\frac{r_0''}{2} \tag{6}$$

and t was corrected according to formula (5). This did not appreciably change the values of r_0, r_0', and r_0''. The convergence of series (3) was rapid enough to give good results when only the first three terms were used. We have, therefore, a number of equations of the type (6). If we assume for t_0 the mean of all times, the solution is especially simple. By subtracting from each equation of condition the mean equation

$$r_0=\bar{r}-\bar{t^2}\frac{r_0''}{2}\,, \tag{7}$$

where the mean values are denoted by the bars, we shall therefore have equations of the type

$$r-\bar{r}=tr_0'+(t^2-\bar{t^2})\frac{r_0''}{2}\,, \tag{8}$$

which are solved by the method of least squares.

Force f is the resultant force of the solar attraction and repulsion on the prominence. The effective repulsive force is evidently equal to $\mu=-(f/k^2)$ if the time is expressed in days, and radius vector in astronomical units. The absolute repulsive force will then be $1-\mu$ times gravitation. The probable error in μ will be proportional to the probable error in f, that is, will be proportional to the probable error in r_0''.

The most complete data on the motion of solar prominences have been published by E. Pettit.[1] The present investigation is based on Pettit's data. References for individual prominences may be found there. The notation for prominences is that of Pettit's paper.

CALCIUM PROMINENCES

These prominences were observed photographically in the H or K line.

[1] *Publications of the Yerkes Observatory*, **3**, Part IV, 1925.

Prominence 1.—Observed by E. Pettit on May 29, 1919. The data[1] for this prominence are given in Table I. Radius vector r is expressed in millions of kilometers, and is counted from the solar surface. The real radius vector is therefore $R+r$, where R is the radius of the sun.

TABLE I

Point	G.M.T.	r	O−C A	O−C B	O−C C	O−C D
			A	B	C	D
1	29.0536	0.150	−0.027	−0.038	−0.002	....
2	.0670	.150	− .017	− .021	− .003	....
3	.0703	.150	− .014	− .018	− .003	....
4	.0776	.153	− .007	− .009	− .001	....
5	.1079	.163	+ .011	+ .014	+ .001	....
6	.1123	.170	+ .018	+ .022	+ .006	....
7	.1178	.170	+ .017	+ .021	+ .004	....
8	.1229	.175	+ .023	+ .025	+ .007	....
9	.1734	.195	+ .014	+ .017	− .007	....
10	.1802	.200	+ .011	+ .014	− .008	....
11	.1882	.210	+ .013	+ .014	− .006	....
12	.1932	.220	+ .017	+ .017	− .001	....
13	.1992	.225	+ .014	+ .014	− .002	....
14	.2180	.250	+ .010	+ .009	+ .002	....
15	.2310	.265	+ .005	+ .001	+ .001	....
16	.2366	.275	+ .004	.000	+0.003	....
17	.2476	.285	− .008	− .012	....	(−0.002)
18	.2599	.305	− .014	− .019	....	+ .005
19	.2664	.310	− .024	− .029	....	− .001
20	.2724	.322	− .027	− .031	....	.000
21	.2792	.335	− .030	− .035	....	− .002
22	.2871	.360	− .026	− .030	....	+ .002
23	.2978	.388	− .028	− .031	....	− .004
24	.3052	.410	− .026	− .029	....	− .008
25	.3315	.545	+ .027	+ .028	....	+ .009
26	.3497	0.640	+0.059	+0.062	....	0.000

Taking twenty-six equations of the form (8) and solving them by the method of least squares, we have the following normal equations (multiplied here and everywhere else in this paper by the factor 10^5):

$$\left.\begin{aligned} 1936r_0' - 15.3r_0'' &= +2422\,, \\ 6.2 &= +51.0\,, \end{aligned}\right\}$$

[1] r for point 9, given by Pettit in the above-mentioned publication as 0.175, is obviously an error, as follows from his own graph and from his paper in *Astrophysical Journal*, **50**, 209, 1919.

and the equation (7) for r_0:

$$r_0 = 0.2700 - 0.037 r_0'' ,$$

the origin of time being May 29.2018.

The solution of these equations gives

$$r_0 = 0.2145 ,$$
$$r_0' = 1.369 ,$$
$$r_0'' = 14.983 ,$$

all expressed in millions of kilometers and days. The acceleration r_0'' expressed in astronomical units becomes 0.1001 per day per day. The resultant repulsive force can be found from the modified formula (2):

$$f = (R + r_0)^2 r_0'' .$$

Expressed in astronomical units, $R = 0.00465$ and $r_0 = 0.00143$, so that $f = 3.70 \times 10^{-6}$. Comparing this with the Gaussian constant $k^2 = 2.96 \times 10^{-4}$, we find the effective repulsive force

$$\mu = -\frac{f}{k^2} = -0.0125 ,$$

or the total repulsive force $1 - \mu = 1.0125$ times gravitation.

The same numerical result is obtained by expressing r_0'' in km/sec.^{2}, and comparing this with the force of gravity at a distance r_0 from the surface of the sun. This force is equal to $0.274\,[R/(R+r_0)]^2$ km/sec.^{2} $= 0.1601$ km/sec.^{2} The acceleration $r_0'' = 14.98$ should be divided by $(86{,}400)^2 = 7.46 \times 10^9$ and multiplied by 10^6. This gives $r_0'' = 0.00202$ km/sec.^{2} The ratio of the effective repulsive force to the force of gravitation is therefore $\mu = -(0.00201/0.1601) = -0.0125$, the same as before.

The residuals from this solution are given in Table I, column A. They show a systematic distribution and are entirely too large.

The source of error may be in the omission of higher terms in expansion (3). To take into account the terms of the third order, the times have been corrected according to formula (5). Here r_0 should

be counted from the center of the sun, that is, instead of r_0 we should take $R+r_0=0.9098$. Taking from the first solution the value of r_0'', we have $t_1=t-5.48t^3$.

Forming the normal equations in the usual way, we have solution B:

$$\left.\begin{aligned} 1646r_0'-14.2r_0''&=+2221\ , \\ 6.2\quad &=+51.0\ , \end{aligned}\right\}$$

which yield

$$r_0'=\ 0.2145\ ,$$
$$r_0'=\ 1.479\quad ,$$
$$r_0''=15.000\quad .$$

The value of the repulsive force is identical with that from solution A.

It is seen from the distribution of residuals that solution B (Table I) does not represent the observations any better than A. It is clear

TABLE II

Group	G.M.T.	r	O−C
a.............	29.0671	0.1506	−0.0020
b.............	.1152	.1694	+ .0046
c.............	.1868	.2100	− .0047
d.............	.2285	0.2633	+0.0022

that the motion of matter in this prominence was not under a central repulsive force or else the force itself was not constant.

The latter alternative appears more likely. There is an obvious break of continuity between points 16 and 17 (Fig. 1). It might be possible, therefore, to represent the motion satisfactorily by two curves, one comprising the points from 1 to 16, and the other the rest of the points.

The first partial solution C is based on four groups of points: from 1 to 4, from 5 to 8, from 9 to 13, and from 14 to 16. We have then the data shown in Table II. The last column contains the residuals from the least-squares solution. This includes the terms only of the first and second order in r_0, as the correction in t for the third-order terms is small.

The normal equations are as follows:

$$\left.\begin{aligned} 1560r_0' - 2.64r_0'' &= +1049 , \\ -1.38 \quad &= +6.53 , \end{aligned}\right\}$$

$$r_0 = 0.1983 - 0.00195r_0'' ,$$

which give

$$r_0 = 0.1839 ,$$

$$r_0' = 0.684 \pm 0.028 \text{ (probable error)} ,$$

$$r_0'' = 7.38 \pm 1.31 .$$

The motion of the prominence is represented much better than in the general solutions A and B, as may be seen from the distribution and magnitude of the residuals (col. C of Table I).

The value of the effective repulsive force f comes out $f = 1.71 \times 10^{-6}$, and therefore $\mu = -0.0058 \pm 0.0010$, and $1 - \mu = 1.0058 \pm 0.0010$. The velocity at time $t_0 =$ May 29.1494 is $r_0' = 0.684 \times 10^6$ km/day or $v_0 = 7.9$ km/sec.

It is seen from the diagram (Fig. 1) that even this orbit does not give a completely satisfactory representation of observations. Group *a* seems to be out of harmony with groups *b*, *c*, and *d*. However, orbit C gives a fair idea of the magnitude of the repulsive force in the prominence in the first part of observation.

Taking points 18–26 for orbit D, we find $t_0 =$ May 29.2944. The normal equations are

$$\left.\begin{aligned} 733r_0' + 7.42r_0'' &= +2753 , \\ 0.39 \quad &= +68.3 , \end{aligned}\right\}$$

$$r_0 = 0.4016 - 0.00041r_0'' ,$$

which are satisfied by

$$r_0 = 0.3801 ,$$

$$r_0' = 3.22 \pm 0.05 ,$$

$$r_0'' = 53.2 \pm 3.2 .$$

The residuals are given in column D of Table I. They are evidently much better than from general solutions A and B, in spite of the fact that only derivatives of the first and second order have been

used in solution D. It is clear that the derivatives of the third order are too small to influence the solution, so that in the following solutions they will not be used in the formation of the normal equations unless otherwise stated.

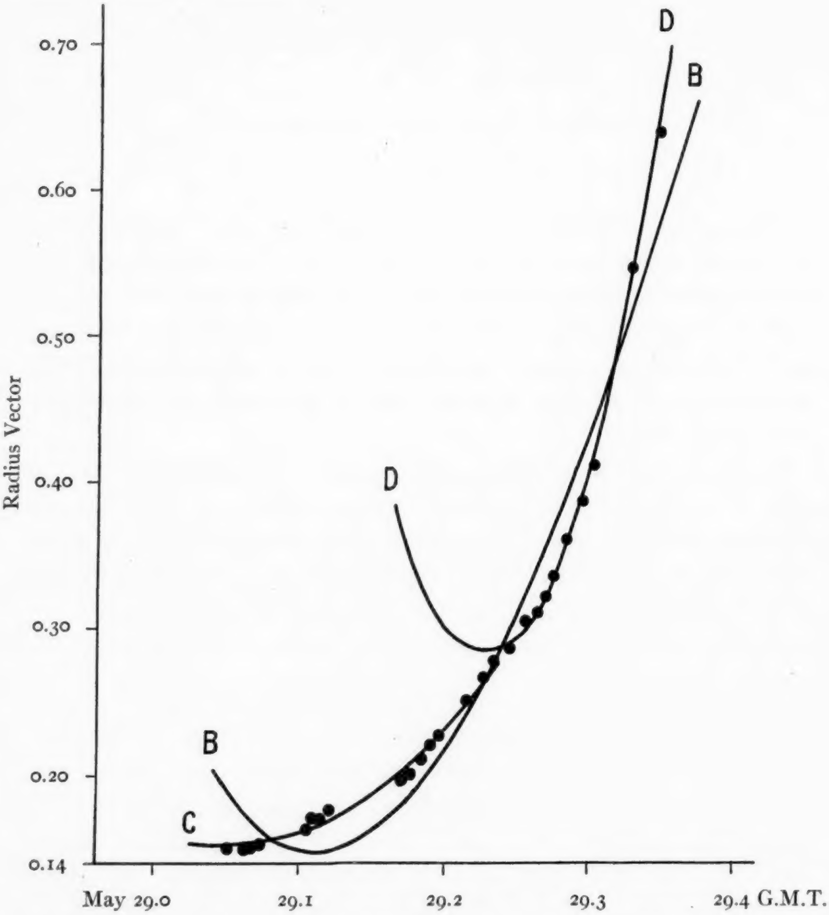


FIG. 1.—Motion of prominence No. 1, general orbit *B*, and partial solutions *C* and *D*. Filled circles represent observed points. Ordinate, distance from the surface of the sun in million kilometers; abscissa, G.M.T.

We obtain for orbit D, $f=1.845\times10^{-5}$, $1-\mu=1.0622\pm0.0037$, $v_0=37.3$ km/sec. Point 17 was not included in the solution, but it apparently belongs to this orbit.

It appears that this prominence moved under at least two repulsive forces, $1-\mu=1.0058$ and $1-\mu=1.0623$. Comparatively small increase in the absolute value of the repulsive force was sufficient to change very considerably its orbit and its average velocity.

Prominence 3.—Observed by Pettit on September 8, 1919. The data are given in Table III. Taking points 1 and 2, mean of 3 and 4,

TABLE III

Point	G.M.T.	r	O−C
1	8.1080	0.085	−0.004
2	.1263	.093	+ .005
3	.1500	.095	+ .001
4	.1518	.097	+ .002
5	.1570	.101	+ .002
6	.1576	.103	+ .004
7	.1816	.116	− .005
8	.1904	.128	− .004
9	.1925	.131	− .004
10	.2612	.286	+ .008
11	.2663	.301	+ .008
12	.2786	.321	− .008
13	.2850	0.348	−0.002

mean of 5 and 6, point 7, mean of 8 and 9, mean of 10 and 11, mean of 12 and 13, we have eight equations of condition resulting in the normal equations

$$\left.\begin{aligned} 2689r_0'+43.4r_0'' &= +4082\,, \\ 4.62 &= +196.6\,, \end{aligned}\right\}$$

$$r_0=0.1562-0.00168r_0''\,.$$

The origin of time is September 8.1826. The solution of the normal equations gives

$$r_0=\ 0.1224\,,$$

$$r_0'=\ 1.191\pm0.028\,,$$

$$r_0''=20.1\pm1.0\,,$$

This results in $f=4.02\times10^{-6}$, $1-\mu=1.0136\pm0.0007$, $v_0=13.8$ km/sec. The residuals for the original points of observation are given in Table III. The orbit is quite satisfactory.

Settings were made on the center of the prominence's head. Pettit gives also measurements for a condensation near the middle of the prominence. This moved with the same velocity as the corresponding points of the main prominence, and presumably under the same $1-\mu$.

Prominence 4.—Observed by O. J. Lee on February 19, 1920. The data are as shown in Table IV.

TABLE IV

Point	G.M.T.	r	O−C	
			A	B
1	19.1658	0.110	+0.001	....
2	.2000	.144	.000	....
3	.2059	.148	− .002	....
4	.2071	.152	.000	....
5	.2242	.171	− .003	....
6	.2253	.175	.000	....
7	.2305	.186	+ .004	....
8	.2326	.186	+ .001	....
9	.2479	.205	− .002	....
10	.2492	.209	.000	....
11	.3085	.311	− .003	....
12	.3094	.319	+0.003	....
13	.3151	.322	....	−0.002
14	.3161	.326	....	+ .004
15	.3302	.334	....	+ .013
16	.3313	.341	....	+ .017
17	.3441	.387	....	− .006
18	.3464	0.387	....	−0.025

It is apparent from the graph that no single curve can satisfy the whole series of observations. A break occurs between points 12 and 13. The first part of the series is represented by orbit A, the second by orbit B.

Taking point 1, the mean of points 2, 3, and 4, then the means of the following pairs of points, we obtain for orbit A six equations of condition. The origin of time is February 19.2306. The normal equations are

$$\left.\begin{aligned} 1139r_0'+9.86r_0'' &= +1651\,, \\ 1.72 &= +41.1\,, \end{aligned}\right\}$$

$$r_0=0.1898-0.00095r_0''\,.$$

They are solved as follows:

$$r_0 = 0.1822\ ,$$
$$r_0' = 1.384 \pm 0.012\ ,$$
$$r_0'' = 8.04 \pm 0.40\ ,$$

which gives $f = 1.852 \times 10^{-6}$, $1 - \mu = 1.0063 \pm 0.0003$, $v_0 = 16.0$ km/sec.

For orbit B we have three pairs of observations which give normal equations (the origin of time t_0 = February 19.3305)

$$\left.\begin{aligned} 43.8r_0' - 0.066r_0'' &= +93.0\ , \\ 0.0016 &= +0.244\ , \end{aligned}\right\}$$
$$r_0 = 0.3495 - 0.000073r_0''\ ,$$

satisfied by

$$r_0 = 0.3220\ ,$$
$$r_0' = 2.68 \pm 0.44\ ,$$
$$r_0'' = 376 \pm 104\ .$$

These give $f = 1.160 \times 10^{-4}$, $1 - \mu = 1.396 \pm 0.108$, $v_0 = 31$ km/sec.

The residuals for the original observations are given in Table IV. Orbit A is evidently quite reliable. Orbit B gives only a rough idea

TABLE V

Point	G.M.T.	r	O−C
1	21.1368	0.106	−0.002
2	.1628	.123	+ .001
3	.1642	.129	+ .005
4	.1785	.144	+ .001
5	.1797	.145	.000
6	.2008	.186	− .004
7	.2019	.189	− .004
8	.2066	.199	− .002
9	.2074	.204	− .002
10	.2123	.220	+ .001
11	.2135	.234	+ .009
12	.2316	.293	+ .006
13	.2330	0.292	−0.002

of the repulsive force at the end of observation. There is no doubt that it was much greater than at the beginning.

Prominence 5.—Observed by Lee on October 21, 1914. The data are as shown in Table V. Taking point 1 and the mean of the subsequent pairs of points, we obtain eight equations of condition which result in the normal equations (the origin of time t_0=October 21.1904)

$$\left.\begin{aligned} 639r_0'-4.19r_0'' &= +1199\ , \\ 0.319 &= -5.22\ , \end{aligned}\right\}$$

$$r_0=0.1837-0.00045r_0''\ .$$

which are satisfied by

$$r_0=\ 0.1656\ ,$$

$$r_0'=\ 2.13\pm0.03\ ,$$

$$r_0''=39.74\pm1.99\ .$$

From these values we obtain $f=8.82\times10^{-6}$, $1-\mu=1.0298\pm0.0015$, $v_0=24.7$ km/sec. The residuals for the original observations are given in Table V. They are of an acceptable order of magnitude.

This prominence was observed by Lee[1] on October 19 and 20 and was apparently of a quiescent type. The eruption occurred on

TABLE VI

Point	G.M.T.	r	O−C
1	25.1214	0.038	+0.007
2	.1769	.053	− .015
3	.1783	.068	− .001
4	.2056	.103	− .034
5	.2069	.148	+ .007
6	.2157	.174	+ .004
7	.2382	.276	+ .018
8	.2396	.287	+ .023
9	.2468	.295	− .002
10	.2484	0.295	−0.009

October 21. Even during the eruption one part of the prominence remained stationary.

Prominence 6.—Observed by F. Slocum on March 25, 1910. The data are as shown in Table VI. Taking point 1 and the mean of

[1] *Astrophysical Journal*, **41**, 168, 1915.

points 2 and 3; 4, 5, and 6; 7, 8, 9, and 10, we have four equations of condition with t_0 = March 25.1879. The normal equations are

$$\left.\begin{aligned} 805r_0' - 5.79r_0'' &= +1586\,, \\ 0.546 &= +0.58\,, \end{aligned}\right\}$$

$$r_0 = 0.1321 - 0.00101r_0''\,.$$

These yield

$$r_0 = \ 0.0903\,,$$

$$r_0' = \ 2.27 \pm 0.09\,,$$

$$r_0'' = 41.6 \pm 4.5\,.$$

From these values we obtain $f = 7.69 \times 10^{-6}$, $1 - \mu = 1.0260 \pm 0.0028$, $v_0 = 26.3$ km/sec. This prominence was observed by Slocum[1] on March 24, but no signs of activity were noticed. The region under the prominence was free from any unusual disturbance. The closest approach to the surface of the sun occurred between points 1 and 2, so that the eruption could not have begun on March 24.

TABLE VII

Point	G.M.T.	r	O−C
1.............	21.1681	0.169	0.000
2.............	.2028	.190	− .001
3.............	.2090	.206	+ .001
2.............	.2326	.287	− .001
5.............	.2340	.294	− .001
6.............	.2382	0.317	+0.002

Prominence 7.—Observed by P. Fox on May 21, 1907. The data are as shown in Table VII. The origin of time is May 21.2141. The normal equations are

$$\left.\begin{aligned} 360r_0' - 3.55r_0'' &= +780\,, \\ 0.148 &= -8.96\,, \end{aligned}\right\}$$

$$r_0 = 0.2438 - 0.00030r_0''\,.$$

[1] *Ibid.*, **32**, 128, 1910.

The solution of these equations gives

$$r_0 = 0.2191 ,$$

$$r_0' = 2.98 \pm 0.02 ,$$

$$r_0'' = 82.4 \pm 1.7 .$$

From these values we obtain $f = 2.07 \times 10^{-5}$, $1 - \mu = 1.0698 \pm 0.0034$, $v_0 = 34.5$ km/sec. The remaining seven points of this prominence cannot be reconciled with this orbit. Apparently the process of disintegration had already set in. Even earlier, between points 1 and 2, the prominence was found to be split into branches.[1]

Prominence 8.—Observed by J. Evershed on February 18, 1908. The data are given in Table VIII. It is obvious that the motion of

TABLE VIII

Point	G.M.T.	r	O−C A	O−C B
1	18.1201	0.058	+0.001	....
2	.1722	.069	− .002	....
3	.1833	.077	+ .002	....
4	.1882	.077	.000	....
5	.2326	.096	+ .001	....
6	.2382	.096	−0.002	....
7	.3750	.113	....	+0.006
8	.3792	.113	....	+ .006
9	.4410	.144	....	− .014
10	.4444	.154	....	− .009
11	.4868	.234	....	− .010
12	.4910	.261	....	+ .007
13	.5014	.290	....	+ .010
14	.5076	0.301	....	+0.004

the prominence cannot be represented by a single orbit. The first six points gave orbit A, the remaining eight orbit B.

For orbit A, t_0 = February 18.1891. The normal equations are

$$\left.\begin{aligned} 938r_0' - 6.7r_0'' &= +321 , \\ 0.872 &= -2.82 , \end{aligned}\right\}$$

$$r_0 = 0.0788 - 0.00078 r_0'' .$$

[1] *Ibid.*, **26**, 155, 1907.

The values of the unknowns are

$$r_0 = 0.0770\,,$$
$$r_0' = 0.358 \pm 0.031\,,$$
$$r_0'' = 2.71 \pm 0.64\,.$$

These give $f = 4.05 \times 10^{-7}$, $1 - \mu = 1.0014 \pm 0.0004$, $v_0 = 4.1$ km/sec.

For orbit B, $t_0 =$ February 18.4533. The normal equations,

$$\left.\begin{aligned} 1965r_0' - 52.5r_0'' &= +2763\,, \\ 3.68 &= -51.5\,, \end{aligned}\right\}$$
$$r_0 = 0.2013 - 0.00123r_0''\,,$$

are satisfied by

$$r_0 = 0.1771\,,$$
$$r_0' = 1.670 \pm 0.062\,,$$
$$r_0'' = 19.62 \pm 2.88\,,$$

which give $f = 4.47 \times 10^{-6}$, $1 - \mu = 1.0151 \pm 0.0022$, $v_0 = 19.3$ km/sec.

Prominence 9.—Observed by Evershed on May 26, 1916. The data are as shown in Table IX. Point 1 cannot be reconciled with

TABLE IX

Point	G.M.T.	r	O−C
1	26.1084	0.102	(−0.056)
2	.1193	.166	+ .002
3	.1295	.220	− .011
4	.1364	.322	+ .005
5	.1394	.372	+ .008
6	.1435	.440	+ .001
7	.1481	.524	− .012
8	.1524	0.643	+0.004

the rest of the observations. It was not considered in the formation of the equations of condition. The origin of time is May 26.1384. The normal equations

$$\left.\begin{aligned} 76.5r_0' - 0.193r_0'' &= +1105\,, \\ 0.00519 &= -2.80\,, \end{aligned}\right\}$$
$$r_0 = 0.3838 - 0.000054r_0''\,,$$

are satisfied by

$$r_0 = 0.3480\,,$$
$$r_0' = 16.20 \pm 0.24\,,$$
$$r_0'' = 658 \pm 40\,.$$

These give $f = 2.14 \times 10^{-4}$, $1 - \mu = 1.723 \pm 0.044$, $v_0 = 187$ km/sec.

Prominence 10.—Observed by H. Deslandres on May 31, 1894.

TABLE X

Point	G.M.T.	r	O−C
1	31.0799	0.103	0.000
2	.1792	.220	.000
3	.2021	.323	+ .007
4	.2299	0.458	−0.008

The data are as shown in Table X. The origin of time is $t_0 =$ May 31.1728. The normal equations are

$$\left.\begin{aligned} 1277 r_0' - 29.7 r_0'' &= +2748\,, \\ 2.24 &= -86.0\,, \end{aligned}\right\}$$
$$r_0 = 0.2760 - 0.00160 r_0''\,.$$

The solution of these equations is

$$r_0 = 0.1983\,,$$
$$r_0' = 3.29 \pm 0.07\,,$$
$$r_0'' = 48.8 \pm 2.5\,,$$

which values give $f = 1.164 \times 10^{-5}$, $1 - \mu = 1.0395 \pm 0.0020$, $v_0 = 38.1$ km/sec.

Prominence 11.—Observed by G. Hale and F. Ellerman on March 25, 1895. The data are as shown in Table XI. The normal equations are

$$\left.\begin{aligned} 129.4 r_0' - 2.09 r_0'' &= +879\,, \\ 0.0294 &= -10.41\,, \end{aligned}\right\}$$
$$r_0 = 0.2630 - 0.000130 r_0''\,.$$

They are satisfied by

$$r_0 = 0.2089\,,$$
$$r_0' = 10.32 \pm 0.25\,,$$
$$r_0'' = 418 \pm 22\,.$$

From these values we obtain $f = 1.026 \times 10^{-4}$, $1 - \mu = 1.346 \pm 0.019$, $v_0 = 120$ km/sec.

TABLE XI

Point	G.M.T.	r	O−C
1	25.1529	0.087	0.000
2	.1833	.216	+ .005
3	.1875	.259	+ .001
4	.1917	.303	− .011
5	.2000	0.450	+0.007

HYDROGEN PROMINENCES

These prominences were observed visually in the $H\alpha$ line.

Prominence 13.—Observed by Fényi on September 6, 1888. The

TABLE XII

Point	G.M.T.	r	O−C
1	6.1840	0.015	0.000
2	.2014	.018	− .001
3	.2028	.033	+ .004
4	.2049	.043	− .003
5	.2076	.068	− .005
6	.2104	0.110	+0.005

data are as shown in Table XII. The origin of time is September 6.2018. The normal equations are

$$\left.\begin{aligned} 43.6r_0' - 0.241r_0'' &= +121.8\,, \\ .00384 &= -0.527\,, \end{aligned}\right\}$$
$$r_0 = 0.0478 - 0.000037r_0''\,.$$

These equations are satisfied by the following values of the unknowns:

$$r_0 = 0.0220\,,$$
$$r_0' = 6.66 \pm 0.24\,,$$
$$r_0'' = 706 \pm 37\,,$$

which give $f = 1.086 \times 10^{-4}$, $1-\mu = 1.367 \pm 0.019$, $v_0 = 77.3$ km/sec. It is of interest to note that the curve will intersect the surface of the sun; its vertex is some 0.02 million kilometers below the surface. However, if point 1 is neglected, the solution is exactly the same.

Prominence 14.—Observed by P. J. Fényi on October 6, 1890.

TABLE XIII

Point	G.M.T.	r	O−C
1	6.0014	0.040	−0.005
2	.0049	.050	+ .003
3	.0072	.066	+ .010
4	.0090	.076	+ .008
5	.0135	.100	− .015
6	.0146	.123	− .006
7	.0160	.148	+ .001
8	.0188	0.206	+0.008

The data are as shown in Table XIII. The origin of time is October 6.0107. The normal equations are

$$\left.\begin{aligned} 25.16r_0' - 0.01411r_0'' &= +221.2\,, \\ 0.000313 &= +0.098\,, \end{aligned}\right\}$$

$$r_0 = 0.1011 - 0.0000157r_0''\,.$$

They are satisfied by

$$\begin{aligned} r_0 &= 0.0828\,, \\ r_0' &= 9.45 \pm 0.40\,, \\ r_0'' &= 1168 \pm 161\,. \end{aligned}$$

These values give $f = 2.11 \times 10^{-4}$, $1-\mu = 1.714 \pm 0.098$, $v_0 = 109$ km/sec. The original observations include two more points which evidently do not belong to this series. They show a decrease in velocity.

Prominence 15.—Observed by Fényi on May 5, 1892. The data are as shown in Table XIV. The first solution gave $r_0 = 0.2018$, $r_0' = 18.32$, $r_0'' = 1628$. In view of the high value of r_0'', a second solution, including the terms of the third order, was made. The times

(t_0 = May 5.4596) at r_0' have been corrected by $-605t^3$. The normal equations are

$$\left.\begin{aligned} 27.4r_0' - 0.142r_0'' &= +\ 338\,, \\ 0.00243 &= -2.13\,, \end{aligned}\right\}$$

$$r_0 = 0.2490 - 0.0003r_0' - 0.000029r_0''\,.$$

The solution of these equations gives

$$r_0 = \quad 0.2009\,,$$
$$r_0' = \quad 19.9 \pm 1.6\,,$$
$$r_0'' = 1454 \pm 240\,.$$

The residuals are given in Table XIV. They are practically the same as for the first solution.

TABLE XIV

Point	G.M.T.	r	O−C
1	5.4437	0.102	−0.024
2	.4590	.209	+ .020
3	.4602	.231	+ .018
4	.4620	.269	+ .016
5	.4646	.295	− .022
6	.4678	0.388	−0.019

We have $f = 3.48 \times 10^{-4}$, $1 - \mu = 2.18 \pm 0.19$, $v_0 = 231$ km/sec.

Prominence 18.—Observed by Fényi on December 24, 1894. The data are as shown in Table XV. Taking point 1, mean of points 2–8, 9–12, 13 and 14, 15 and 16, 17 and 18, we have six equations of condition which give the normal equations

$$\left.\begin{aligned} 323r_0' - 5.31r_0'' &= +1633\,, \\ 0.215 &= -39.3\,, \end{aligned}\right\}$$

$$r_0 = 0.2914 - 0.00027r_0''\,.$$

The solution of these equations gives

$$r_0 = \quad 0.1980\,,$$
$$r_0' = \quad 10.7 \pm 0.4\,,$$
$$r_0'' = 346 \pm 24\,.$$

With these values we obtain $f=8.30\times 10^{-5}$, $1-\mu=1.281\pm 0.020$, $v_0=124$ km/sec. The remaining eight points show a gradual decrease in the height of the prominence. Apparently it fell back on the surface of the sun.

TABLE XV

Point	G.M.T.	r	O−C
1	24.3854	0.088	0.000
2	.4292	.151	+ .005
3	.4295	.148	− .002
4	.4299	.156	+ .003
5	.4302	.160	+ .005
6	.4306	.150	− .009
7	.4309	.154	− .007
8	.4401	.266	+ .003
9	.4406	.276	+ .007
10	.4412	.288	+ .009
11	.4417	.297	+ .013
12	.4424	.309	+ .015
13	.4455	.369	+ .032
14	.4464	.364	+ .014
15	.4500	.388	− .016
16	.4509	.404	− .016
17	.4528	.445	− .007
18	.4551	0.470	−0.022

TABLE XVI

Point	G.M.T.	r	O−C
1	24.8882	0.010	0.000
2	.9174	.064	+ .003
3	.9306	0.095	−0.002

Prominence 21.—Observed by J. Sykora on August 24, 1893. The data are as shown in Table XVI. The normal equations are

$$\left.\begin{aligned} 94.1r_0'-0.357r_0'' &= +186.5\,, \\ 0.000743 &= -1.202\,, \end{aligned}\right\}$$

$$r_0=0.0563-0.000157r_0''\,.$$

The origin of time is August 24.9121. The solution of the normal equations gives

$$r_0=\ 0.0493\,,$$

$$r_0'=\ 2.16\pm 0.09\,,$$

$$r_0''=44.8\pm 14.9\,.$$

With these values we obtain $f=7.44\times 10^{-6}$, $1-\mu=1.0251\pm 0.0083$, $v_0=24.9$ km/sec.

The fourth point given by the observer ($r=0.079$) shows a change in the motion of the prominence.

Prominence 22.—Observed by P. Tacchini on November 16, 1892. The data are as shown in Table XVII. All the observations cannot be represented by a single curve. The first four points lie on a straight line. Furthermore, r for point 8 is obviously in error, as is clear from

TABLE XVII

Point	G.M.T.	r	O−C
1	16.3403	0.094	....
2	.3611	.104	....
3	.3840	.113	....
4	.4125	.124	....
5	.4444	.142	−0.006
6	.4618	.152	+ .009
7	.4931	.201	+ .003
8	.5021	.288	....
9	.5097	.247	− .012
10	.5201	.307	− .003
11	.5257	.332	− .009
12	.5292	.367	+ .005
13	.5299	.382	+ .016
14	.5306	.382	+ .012
15	.5313	0.382	+0.007

Pettit's diagram. Neglecting the first four points and point 8, and combining the last three observations into a single one, we have eight equations of condition with $t_0=$ November 16.5018. The normal equations are

$$\left.\begin{aligned} 751r_0'-9.4r_0''&=+2052\,, \\ 0.401&=-37.6\,, \end{aligned}\right\}$$

$$r_0=0.2663-0.0047r_0''\,.$$

The solution of these equations gives

$$r_0=0.2272,$$

$$r_0'=3.77\pm 0.12\,,$$

$$r_0''=83.0\pm 7.1\,,$$

from which we obtain $f=2.11\times 10^{-5}$, $1-\mu=1.0715\pm 0.0061$, $v_0=43.7$ km/sec.

Prominence 23.—Observed by J. B. Coit on June 11, 1895. The data are as shown in Table XVIII. It is evident that the whole series of observations cannot be represented by a single orbit. Points 4, 5, 6, and 7 lie on a straight line, while points 1, 2, and 3 give orbit A, and points 8, 9, 10, 11, and 12 give orbit B.

TABLE XVIII

Point	G.M.T.	r	O−C
1	11.3035	0.054	0.000
2	.3167	.063	.000
3	.3299	.086	.000
4	.3329	.122	....
5	.3336	.131	....
6	.3343	.145	....
7	.3354	.154	....
8	.3382	.179	.000
9	.3417	.185	− .002
10	.3431	.195	+ .002
11	.3454	.203	.000
12	.3469	0.212	0.000

ORBIT A

The origin of time is June 11.3167. The normal equations are

$$\left.\begin{aligned}34.84r_0'+0.000000r_0''&=+42.5\,,\\ 0.001012\quad&=+0.0185\,,\end{aligned}\right\}$$

$$r_0=0.0677-0.0000580r_0''\,.$$

The solution of these equations gives

$$\begin{aligned}r_0&=\ 0.0630\,,\\ r_0'&=\ 1.219\pm0.000\,,\\ r_0''&=80.5\ \ \pm1.3\,,\end{aligned}$$

From these values we obtain $f=1.384\times10^{-5}$, $1-\mu=1.0467\pm0.0008$, $v_0=14.1$ km/sec.

ORBIT B

The origin of time is June 11.3431. The normal equations are

$$\left.\begin{aligned}4.57r_0'-0.00258r_0''&=+17.55\,,\\ 0.000199&=-0.011\,,\end{aligned}\right\}$$

$$r_0=0.1948-0.00000457r_0''\,.$$

The values of the unknowns are

$$r_0 = 0.1925\,,$$
$$r_0' = 4.14 \pm 0.21\,,$$
$$r_0'' = 518 \pm 142\,,$$

which give $f = 1.223 \times 10^{-4}$, $1 - \mu = 1.413 \pm 0.114$, $v_0 = 48.9$ km/sec.

Figure 2 represents the motion of the prominence. It seems that it began moving under $1 - \mu = 1.0467$ with a velocity of 14 km/sec.;

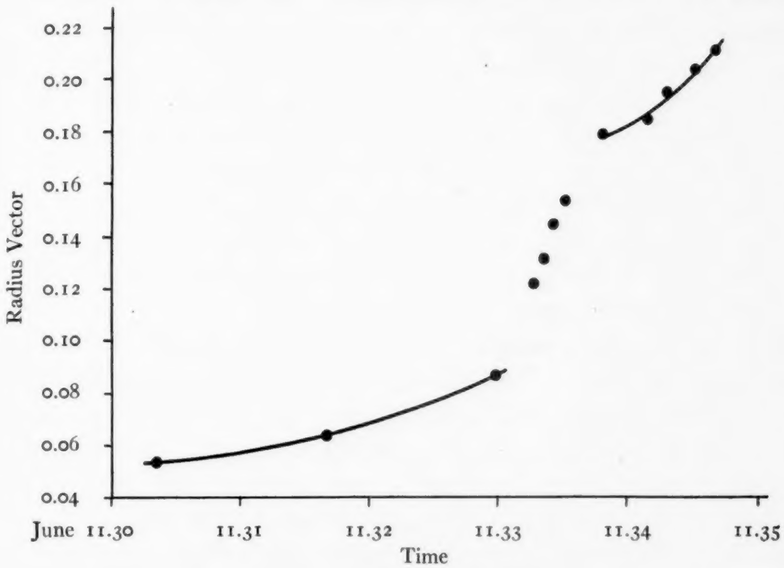


FIG. 2.—Motion of prominence No. 23. Abscissa, G.M.T.; ordinate, distance from the surface of the sun in million kilometers.

then the effective repulsive force diminished to zero and the prominence moved under inertia with a much higher speed of the order of 150 km/sec.; after which the repulsive force suddenly increased again to 1.413, but the velocity decreased to 49 km/sec. Evidently there were at least two internal transformations in the prominence.

The remaining seven prominences in Pettit's collection show such irregular motions that the repulsive force cannot be calculated. They can best be represented as was done by Pettit by broken straight lines, that is, by uniform motion with sudden changes in velocity.

DISCUSSION OF RESULTS

No precise determination of the effective repulsive force μ acting on the prominence is possible. For the calcium prominences the average probable error in the value of the effective repulsive force is 9.2 per cent, if we exclude the doubtful case No. 4B. Including this, we obtain the average probable error of 10.6 per cent. For the hydrogen prominences this probable error is 14.7 per cent. This, of course, should be attributed to the greater uncertainty of visual observations as compared with the photographic. But since the effective repulsive force μ is a small fraction of the total repulsive force $1-\mu$, the probable errors in percentage of $1-\mu$ are small: 1.2 per cent for the calcium and 4.0 per cent for the hydrogen prominences. The average probable error in velocity for the calcium prominences, excluding 4B, is 2.8 per cent, and including 4B is 3.8 per cent. For the hydrogen prominences it amounts to 4.1 per cent. Since in all cases but one (No. 15) $1-\mu$ lies between 1 and 2, it follows that the total repulsive force acting on the prominences can be determined to a sufficient degree of approximation to be useful.

Table XIX gives a summary of results obtained from the individual prominences.[1] The data of Table XVIII are represented graphically in Figures 3 and 4. In Figure 3 the repulsive forces are plotted against the radius vector r_0 corresponding to t_0, the mean of the times of observation. Although t_0, and consequently r_0, depends on the distribution of observation, nevertheless this graph gives a good idea of the variation of the repulsive force with the distance from the solar surface. Measures of the height of prominences were on the average uniformly distributed throughout the time of observation.

We find first that $1-\mu$, for both calcium and hydrogen, shows large variations with r_0. It is clear, however, that the repulsive force increases with the distance from the surface of the sun. More reliable figures can be obtained by averaging the repulsive forces within certain limits of r_0. This is given in Table XX.

It is seen that the repulsive forces acting on hydrogen are always

[1] For some of these prominences rough estimates of the effective repulsive forces were made by S. R. Pike, *Monthly Notices of the Royal Astronomical Society*, **88**, 3, 1927. They are in approximate agreement with those of Table XIX.

larger than those acting on calcium. The mean of all determinations gives $1-\mu=1.133$ for calcium and 1.387 for hydrogen, that is, the

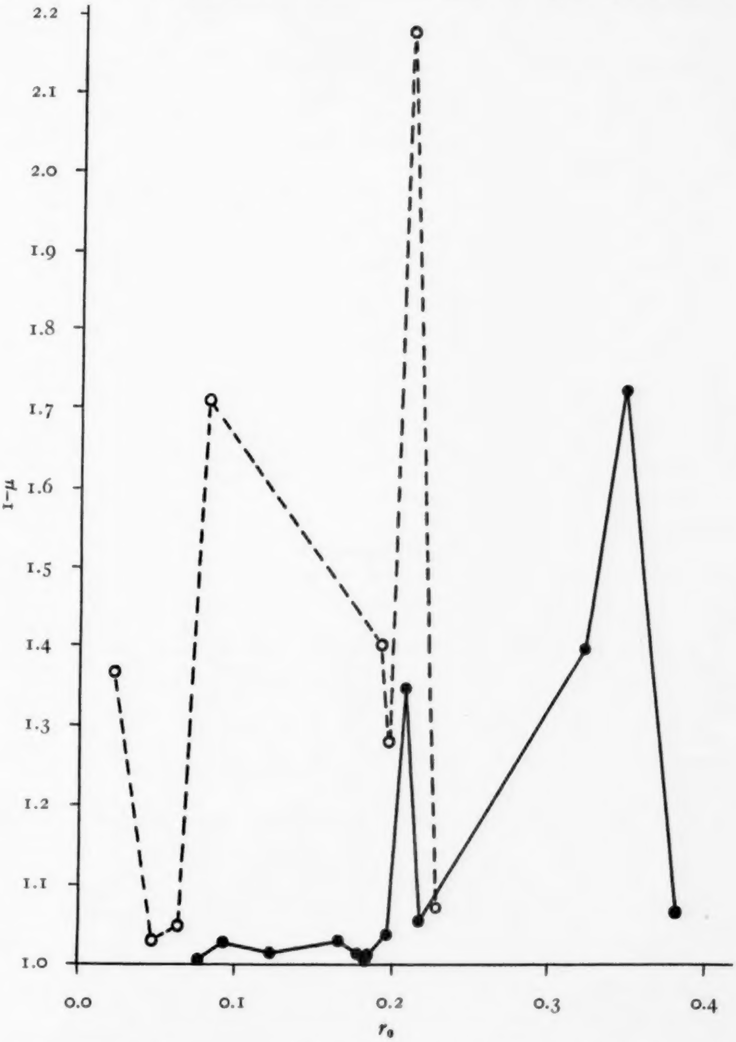


FIG. 3.—Repulsive forces (ordinate) in terms of the force of gravitation against mean distances from the sun in million kilometers (abscissa). Filled circles represent calcium prominences; open circles, hydrogen prominences.

effective repulsive force, μ, for hydrogen is almost three times as large as for calcium.

The most probable explanation of the dependence of the repulsive force on the distance from the solar surface is the increase in velocity of the prominences with their recession from the sun. We have, therefore, to consider the dependence of the repulsive force on the velocity v_0.

TABLE XIX

No.	$1-\mu$	P.E.	r	v_0 Km/Sec.
Calcium Prominences				
1A	1.0058	±0.0010	0.1839	7.9
1B	1.0622	.0037	.3801	37.3
3	1.0136	.0007	.1224	13.8
4A	1.0063	.0003	.1822	16.0
4B	1.396	.108	.3220	31.
5	1.0298	.0015	.1656	24.7
6	1.0260	.0028	.0903	26.3
7	1.0698	.0034	.2191	34.5
8A	1.0014	.0003	.0770	4.1
8B	1.0151	.0022	.1771	19.3
9	1.723	.044	.3480	187
10	1.0395	.0020	.1983	38.1
11	1.346	±0.019	0.2089	120
Mean	1.133	±0.014	....	....
Hydrogen Prominences				
13	1.367	±0.019	0.0220	77.3
14	1.714	.098	.0828	109
15	2.18	.19	.2009	231
18	1.281	.020	.1980	124
21	1.0251	.0082	.0493	24.9
22	1.0715	.0061	.2272	43.7
23A	1.0467	.0008	.0630	14.1
23B	1.413	±0.114	0.1925	48.9
Mean	1.387	±0.057	....	....

TABLE XX

Limits of r_0		0.0–0.1	0.1–0.2	0.2–0.3	0.3–0.4
Calcium	No. of cases	2	6	2	3
	Average $1-\mu$	1.014	1.018	1.208	1.394
Hydrogen	No. of cases	4	2	2	....
	Average $1-\mu$	1.288	1.347	1.626	....

Velocity, v_0, in the uniformly accelerated motion is

$$v_0 = v_e + \mu(t_0 + t_e) , \tag{9}$$

where v_e and t_e are the velocity and time of ejection, and μ is the effective repulsive force (expressed in the same units as v and t). If

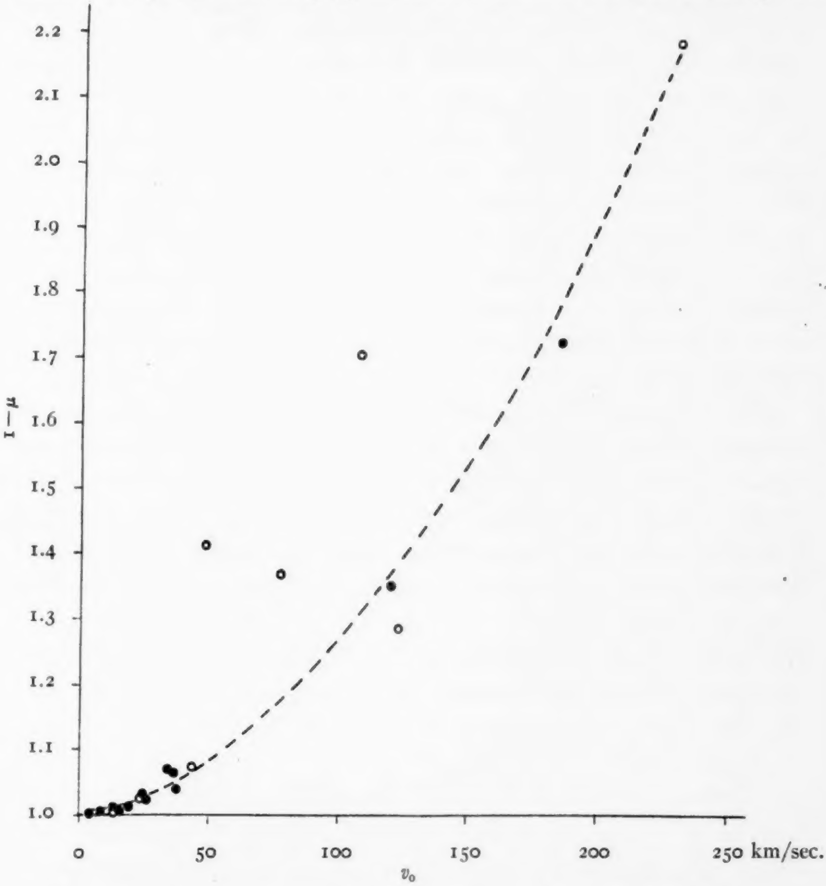


FIG. 4.—Repulsive force $(1-\mu)$ in terms of the force of gravitation as a function of mean velocity v_0 (in km/sec.). Calcium prominences are denoted by filled circles, hydrogen prominences by open circles.

we assume that v_e and $t_0 - t_e$ average themselves for a large number of prominences, then plotting μ (or $1-\mu$) against v_0, we may expect a straight line, the intersection of which, with the v_0—Axis, will give the average velocity of ejection v_e.

This was done in Figure 4. We see that instead of a straight line

we have a very marked curve. The largest deviations are due to hydrogen prominences Nos. 23B, 13, 14, all with large probable errors in both $(1-\mu)$ and v_0. They should be given small weight. Both calcium and hydrogen prominences can be represented by the same curve.

We may interpret Figure 4 in two ways. First, the velocity of ejection of prominences actually increases with the repulsive force to which they are subject. It would be of the order of several km/sec. for the well-defined group of prominences with $1-\mu<1.1$, and of the order of 70 km/sec. for the prominence with repulsive forces $1-\mu=2.0$. Such was the hypothesis put forward by Th. Bredichin in his theory of comets. It would, however, be difficult to explain why the force of ejection should depend on the repulsive force, especially if the matter ejected is the same, namely, *Ca* or *H*. The increase in the repulsive force with the distance (Table XX) would also be difficult to interpret.

The other possibility is that the repulsive force depends on the velocity with which the atom is moving. This theory has been developed in detail by E. A. Milne. Indeed, from Figure 4 we see that the curve is strongly convex toward the v_0–Axis, that is, for higher velocities $1-\mu$ is much greater than would be found by extrapolating the approximately straight line in the lower corner of the graph (up to $v_0=25$ km/sec.).

The momentum due to the radiation pressure on an atom in the chromosphere can be expressed[1] as

$$M=\frac{q_2}{q_1}A_{2\rightarrow 1}\frac{C}{8\pi\nu^2}F_\nu\,, \tag{10}$$

where q_1, q_2, are the weights of the states 1 and 2; for the H and K line $q_2/q_1=3$; $A_{2\rightarrow 1}$ is the transition probability, $F_\nu d\nu$ the amount of energy transmitted between ν and $\nu+\Delta\nu$. The rest of the constants have their usual meaning. The radiation pressure is thus pro-

[1] See J. Woltjer, Jr., *Bulletin of the Astronomical Institute of the Netherlands*, **5**, 43, 1929. This formula is only approximate. For a more precise formula see Milne, *Handbuch der Astroph.*, **3**, Part I, 182, 1930.

portional to the residual intensity of the absorption line corresponding to ν. In order to calculate the radiation pressure it is necessary to know the exact contour of the absorption line.

We do not know as yet the residual intensity in the center of the K line. K. Schwarzschild found it 0.09, M. Minnaert 0.07, and Unsöld 0.15, of the continuous spectrum in the vicinity of the line. This uncertainty very seriously affects the theoretical value of the repulsive force calculated from equation (10).

Even the contour[1] of the line is very differently determined by Minnaert and A. Unsöld. For velocity 120 km/sec. the Doppler effect in the K line will be 2.6 A to the violet. Minnaert's curve gives the intensity at this place as 0.28 while Unsöld's curve gives 0.20. The ratio of the intensity at this place to the intensity at the middle of the line is thus, according to Minnaert, 2.8, and, according to Unsöld, 1.9. Since the repulsive force corresponding to zero Doppler effect is very nearly 1.0 (Fig. 4), the repulsive force on the Ca^+ atom moving with the velocity 200 km/sec. should be 2.8 according to Minnaert, and 1.9 according to Unsöld. Figure 4 shows that the repulsive force derived from the average curve will be approximately 1.9; that is, in agreement with Unsöld's value.

An attempt to calculate the repulsive force on the Ca^+ atom has been made by J. Woltjer, Jr. He used formula (10). The most uncertain quantity entering into this formula is F_ν. Woltjer adopted Minnaert's value for the residual intensity of the K line, with the result $1-\mu=1.38$, assuming a constant outward acceleration (i.e., the zero Doppler effect). The corresponding value from Figure 4 is $1-\mu=1.00$. Even the mean of all, $1-\mu$, for the calcium prominences investigated in this paper is 1.13. That is considerably lower than Woltjer's value. By a strange coincidence the mean $1-\mu$ for the hydrogen prominences is 1.39, almost exactly Woltjer's value for the Ca^+ atom.

The departure of the theoretical value from the observed may be due to various causes. First, as Woltjer pointed out himself, the changes of Ca^+ or Ca or Ca^{++} have been neglected. Second, the

[1] See L. d'Azambuja, *Ann. Obs. Paris-Meudon*, **8**, 6, 1930, for the discussion of the data and contours of the line.

transition probability $A_{2\to 1}=1.6\times 10^8$ sec.$^{-1}$ may be in error.[1] Third, both the intensity of the continuous spectrum and the residual intensity of the H and K lines are subject to fluctuations. This consideration, however, can hardly apply to the present case, as Woltjer took a very low value of the residual intensity in the center of the K line. Other values of the residual intensity would make $1-\mu$ still greater.

Another important source of error may lie in the idealization of the problem. We may study the motion of matter in prominences on Ca^+ spectroheliograms, but prominences do not consist of Ca^+ only. According to Pettit,[2] hydrogen and Ca^+ are very thoroughly mixed in prominences. The same may be true of helium and metals. It would be perhaps too much to expect a close agreement of the observed and computed $1-\mu$.

We should, of course, expect a similar correlation between $1-\mu$ and v_0 in hydrogen prominences. This is evident from Figure 4, although the data are more scattered. The residual intensity of the hydrogen lines is even more uncertain than that of the K line. Thus for $H\alpha$, according to H. von Klüber,[3] it is 0.35 and, according to Minnaert,[4] it is only 0.15 of the continuous spectrum.

The current theory of prominences pictures them as a result of a local disturbance in the photosphere. The repulsive force is proportional to F_ν, formula (10), and a chromosphere, more or less steady when F_ν is steady, receives a sudden impulse when F_ν increases in intensity. One important circumstance is generally neglected in this theory. I refer to the sudden changes in the motion of prominences. Pettit is of the opinion that the motion of prominences can best be represented by broken straight lines. We have seen that many of these can tolerably well be represented by parabolas (or

[1] Since $A_{2\to 1}$ is a reciprocal of τ, the average life of the excited atom, we obtain from $\tau=1.8\times 10^{-8}$ sec., given by Milne (*loc. cit.*) for the Ca^+ atom, $A_{2\to 1}=0.6\times 10^8$ sec.$^{-1}$ However, Milne's determination of τ involves the residual intensity of the K line. He used Schwarzchild's value 0.11. Taking Minnaert's value 0.07, we obtain $A_{2\to 1}=0.9\times 10^8$ sec.$^{-1}$, which would considerably reduce the radiation pressure. On the other hand, Unsöld (*Zeitschrift für Physik*, **44**, 793, 1927) on theoretical grounds gives $1-\mu$ for the Ca^+ atom equal to 1.64 times gravity.

[2] *Publications of the Astronomical Society of the Pacific*, **43**, 159, 1931.

[3] *Zeitschrift für Physik*, **44**, 481, 1927. [4] *Ibid.*, **45**, 610, 1927.

near parabolas). But there are some prominences in Pettit's collection (such as No. 2) for which no parabola can be computed. Moreover, even those moving in parabolas often abruptly change their $1-\mu$ and velocity. It is difficult to explain this by the sudden increase of F_ν in the photosphere underlying the prominence. In some cases, like No. 6, not the slightest trace of a disturbance could be detected under the prominence, although the neighboring regions were carefully examined.

We have a direct indication that the changes in the velocity (and presumably in $1-\mu$) are due to secondary eruptions in the prominence itself. Such were prominences No. 9, and especially No. 23. It is difficult to imagine any change in the photosphere that would not affect the portions of the prominence between the crest and the base, but would change the motion of the crest very considerably. The "bomb" prominences of F. Ellerman gives strong evidence for the real occurrence of explosions.

In conclusion, I would like to draw attention to the remarkable analogy between the solar prominences and comets. The motion of matter (CO^+) in the tails of comets is also under the repulsive influence of the sun and the sudden changes in velocity and $1-\mu$ in the tails of comets are quite often observed. There is no doubt that in many cases this is due to some "explosion" when a tail of the quiescent type becomes suddenly twisted and distorted. A very interesting example[1] of this change is the tail of Halley's comet on April 21, 1910. The coronal arches around centers of disturbance are in many ways analogous to the halo around the nuclei of comets.[1]

The problems involved in the physics of the solar atmosphere and of comets are of the same nature. It is possible that a study of prominences may shed some light on the behavior of comets, and vice versa.

Perkins Observatory
Ohio Wesleyan University
May 6, 1931

[1] *Publications of the Astronomical Society of the Pacific*, **42**, 309, 1930.

A PLANE-GRATING SPECTROGRAPH FOR THE RED AND INFRA-RED REGIONS OF STELLAR SPECTRA[1]

By PAUL W. MERRILL

ABSTRACT

A brief *history* of the use of gratings for stellar spectrographs is included in the introduction.

Description of spectrograph.—The *optical parts* consist of a reflecting slit; a $2\frac{1}{2}$-inch telephoto collimator lens of 40 inches equivalent focal length; a Jacomini plane grating having 600 lines per millimeter; and interchangeable camera lenses of various focal lengths. The *mechanical design* is described by Mr. Nichols. The main casting, of aluminum alloy, is in the form of a trussed **V** with a boxlike extension and is very rigid. It is supported in a tubular steel cradle in such a manner as to eliminate cramping and distortion.

Miscellaneous results.—In the *yellow and red regions* numerous lines may be studied to advantage. In spectra of early type these include the detached D lines and emission $H\alpha$, illustrated in Plate VIII. In K and M spectra certain calcium lines show a strong absolute-magnitude effect. Mr. Sanford has used this spectrograph to extend his radial-velocity determinations of N-type stars. Miss Burwell gives data indicating the accuracy of measurement of radial velocities in stars of classes G–M. Plate IX shows the spectrum of Y Canum Venaticorum, class N3, from λ 6800 to λ 7650. The instrument promises to be useful in the *infra-red* as far as λ 8700. Of special interest are the (nebular) forbidden *O* II multiplet near λ 7325, the *O* I triplet λλ 7772–7774–7775, and the strong *Ca* II triplet λλ 8498, 8542, 8662. Numerous *Ti* lines near λ 8400 are strong in the spectrum of *o* Ceti.

To design an efficient stellar spectrograph is not an altogether simple matter; especially is this true when it is to be used for regions of the spectrum in which relatively little experience is available for guidance. It is not always easy even to decide upon the general type, for the relative weight properly assigned to conflicting considerations is a matter of estimate and balanced judgment rather than of calculation.

The one-prism spectrograph is an effective instrument for observations of the blue-violet region, at least for low dispersion. At greater wave-lengths, however, the angular dispersion decreases rapidly, and the use of long-focus camera lenses to overcome too great condensation of the spectrum is not wholly satisfactory: the long camera increases the width as well as the length of the spectrum, and this fact, together with the necessity of using a narrow slit,

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 432.

leads to long exposures. Moreover, a long camera is a poor mechanical feature. The recourse is either to a greater number of prisms or to a grating. For the yellow and red regions my preference, after using both types of instrument, is for the grating, as it appears to have several practical advantages, notably (1) the exposure times are shorter; (2) a longer range of spectrum is obtainable (with full illumination) on one plate; (3) the dispersion is normal; (4) a change from one spectral region to another is more easily made; (5) the spectrograph is smaller and less expensive.

Gratings are not, however, extensively employed in stellar spectrographs in spite of J. E. Keeler's remarkable visual measurements[1] made with them at Mount Hamilton forty years ago and the fact that more recent observations, made photographically, have not been altogether unpromising. In 1905 Hale and Adams[2] tested gratings for the photography of stellar spectra in connection with the Snow telescope on Mount Wilson. The results included a valuable high-dispersion spectrogram of Arcturus, but the exposure times were long and the instrument did not come into regular use for stars. A grating spectrograph attached to the 36-inch Lick refractor was employed by Campbell and Albrecht in 1910 for their observations of Mars,[3] and later by other observers for a few miscellaneous investigations, but has not had extensive use.

In 1913 Mr. Adams tested for stellar spectra a concave grating of one meter focus in a mounting attached to the 60-inch telescope. It could be used either in the Rowland form or with a 40-inch lens to collimate the light. Exposure times were long, however, and flexure interfered with the definition, so that only a few photographs were ever made with this instrument. These were chiefly of the blue-violet region.

J. S. Plaskett's conclusion[4] at Ottawa in 1914, after comparing the performance of gratings and prisms, was that

> although the spectra obtained from the [plane] grating are disappointingly weak . . . . yet even under this handicap it can be used to advantage when the K line

[1] *Publications of the Lick Observatory*, **3**, 161, 1894.

[2] *Mt. Wilson Contr.*, No. 12; *Astrophysical Journal*, **24**, 69, 1906.

[3] *Lick Observatory Bulletins*, **6** (No. 180), 11, 1910.

[4] *Publications of the Dominion Observatory, Ottawa*, **1**, 179, 1916.

is required and if spectra of uniform dispersion are needed. It would also be useful in the red end where prismatic spectra are so unduly compressed.

In 1922, with grating spectrographs attached to the 100-inch telescope on Mount Wilson, the writer began a series of experiments in which the red and infra-red regions were to be photographed with moderate dispersion. The first observations were with the concave grating used by Mr. Adams in 1913 on which the rulings are 600 per millimeter (15,000 per inch) and cover a surface 67 by 72 mm. A 3-inch concave mirror with a radius of curvature 185 cm served instead of a lens to collimate the light. This made it possible to use the second order for the comparison spectrum and for focusing. The dispersion in the first order was 33 A per millimeter. The focal plane of the spectrum was so curved that glass plates were unsuitable and films $1\frac{3}{4}$ by $5\frac{1}{4}$ inches were clamped by a spring against a metal template having the proper curvature. Eleven stellar spectrograms were obtained during the months of May, June, and July, 1922. Several of these were on films stained with dicyanin and extended to about λ 7900, but required long exposures even for the bright stars, the proper duration for Arcturus being about one hour. The definition of these spectrograms was affected by flexure; moreover, in several instances the comparison lines were sharp at one end of the film but double at the other, indicating a change in the length of the film during exposure.

Another series of experiments with a plane grating was begun in 1924. A new grating, ruled by Mr. Jacomini, had an area 68 by 70 mm with 600 lines per millimeter. The diamond edge used in ruling had been shaped to concentrate the light in the first order on one side. The collimator lens was one of 40-inch focus previously used in a one-prism stellar spectrograph, while a 10-inch lens in regular use in the prism spectrograph served as the camera lens. With this arrangement the definition was excellent and a long range of spectrum was in focus on a flat plate. The mounting, of I-beams and flat plates, was not sufficiently rigid and, on the longer exposures, flexure was evidenced by the displacement of the sharply defined neon comparison lines. About 120 spectrograms were obtained, however, during the following two years by Mr. Sanford and the writer, and although difficulty with flexure was encountered

in securing them, they demonstrated the usefulness and efficiency of this type of instrument.

The next step was the design of a new mounting which would properly support the optical parts. The necessity of taking precautions against flexure, thoroughly brought out by the experience with the preliminary mounting, was one of the chief considerations determining the general form of the instrument. Because the grating acts by reflection, it gives to the beam twice its own angular displacement and necessitates extremely rigid supports. It was therefore decided to have the main casting in the form of a well-braced V, the collimator on one side, the camera on the other, with the grating at the vertex. Moreover, to shorten the whole instrument, a telephoto lens was chosen for the collimator. This lens has an equivalent focal length of 40 inches, but the distance from the slit to its rear surface is only 24 inches, thus making the instrument compact and easily braced. In commercial telephoto lenses designed for use in ordinary cameras the central definition is partially sacrificed to give a larger field. A collimator, however, requires no field, but the central definition must be the best possible. We therefore asked the Bausch and Lomb Optical Company to design and construct a lens especially for this purpose. This lens, designed under the supervision of Mr. W. B. Rayton, was promptly delivered and has given satisfactory results. The grating used in the preliminary mounting served until August, 1929, when a new one, also ruled by Mr. Jacomini, having practically the same dimensions but concentrating in the first order on one side a somewhat higher proportion of the light, was substituted for it. Camera lenses with focal lengths of 6, 10, and 18 inches are available, giving dispersions of 111, 66, and 34 A per millimeter, respectively. The following description of the mechanical features of the mounting is by Mr. E. C. Nichols, designing engineer, to whom were intrusted all the details.

"The mechanical features (see Fig. 1) follow the trend of modern spectrograph design, particularly in the method used for mounting, which incorporates the ideas for obtaining minimum deflections developed by Campbell and Wright at the Lick Observatory. The main casting of aluminum alloy is in box-section truss-form designed

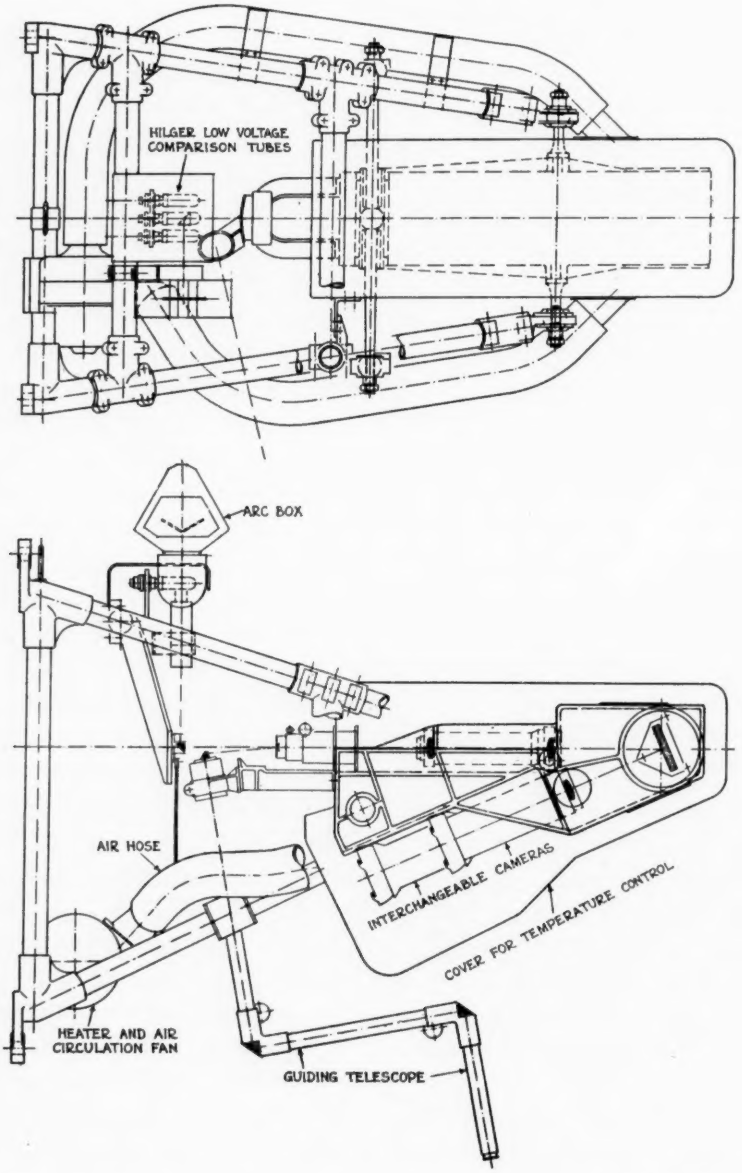


FIG. 1.—Plan and vertical section of plane-grating spectrograph with its supporting framework.

to have the desired stiffness. It is supported at its center of gravity, and carries the slit, collimating lens, grating, and cameras.

"To provide transverse definition the mounting has spindles fastened in opposite sides of the casting which have their outer ends in spherical bearings. Near the slit end of the casting a third supporting point is provided for longitudinal definition and consists of a single spherical bearing. Not only does this arrangement provide a three-point support, giving ideal definition, but the spherical bearings prevent any small deflections in the supporting frame from distorting the spectrograph. These bearings also include adjustments which permit the alignment of the optical axis of the spectrograph with that of the telescope.

"The collimator and camera axes are at a fixed angle of $23\frac{1}{2}°$, the grating being at the apex. This angle, determined approximately by the optical requirements, was as small as mechanically convenient and was one of the factors determining the shape of the main casting.

"The slit of the spectrograph is mounted in a brass tube $2\frac{1}{4}$ inches in diameter, which has adjustments for orientation and a rack and pinion for focusing, with a scale and vernier reading to $\frac{1}{10}$ mm. The polished faces of the slit jaws are inclined $2\frac{1}{2}°$ to permit reflection of a part of the starlight into the prism of the guiding telescope without interfering with the incoming light beam from the telescope.

"The collimator lens is of the telephoto type with an equivalent focus of 40 inches; the distance from the slit to the rear surface of the lens is 24 inches. The lens cell, a tube 12 inches long and $2\frac{5}{8}$ inches in diameter, has turned bearing surfaces at each end, for mounting in standards, fastened and doweled to the main casting. The collimator lens is mounted permanently in position, no focusing adjustment being provided.

"The grating plate, 4 inches square, is in a small mounting rotated by a sector and worm with a scale and vernier reading to six minutes of arc. The squaring and tilting adjustments are made with shims and push screws at the edges and back of the grating. Both grating and mounting are inclosed within a housing incorporated in the spectrograph main casting. A door in the housing permits easy readjustment of the grating.

"The housing is inclosed in an outer cover insulated for temperature, and a space between housing and cover provides for air circulation (see Fig. 1). Openings in the outer cover are so arranged that air entering on one side circulates around all sides of the housing or casting and is discharged on the opposite side into a hose which returns it to the heating coil and circulating fan mounted at the base of the spectrograph support. A double spiral bimetallic thermostat is mounted in the air space outside the housing, with a small door in the outer cover for making adjustments. A thermometer is also mounted in the air space, and a window and small electric lamp provide for convenient reading from the outside.

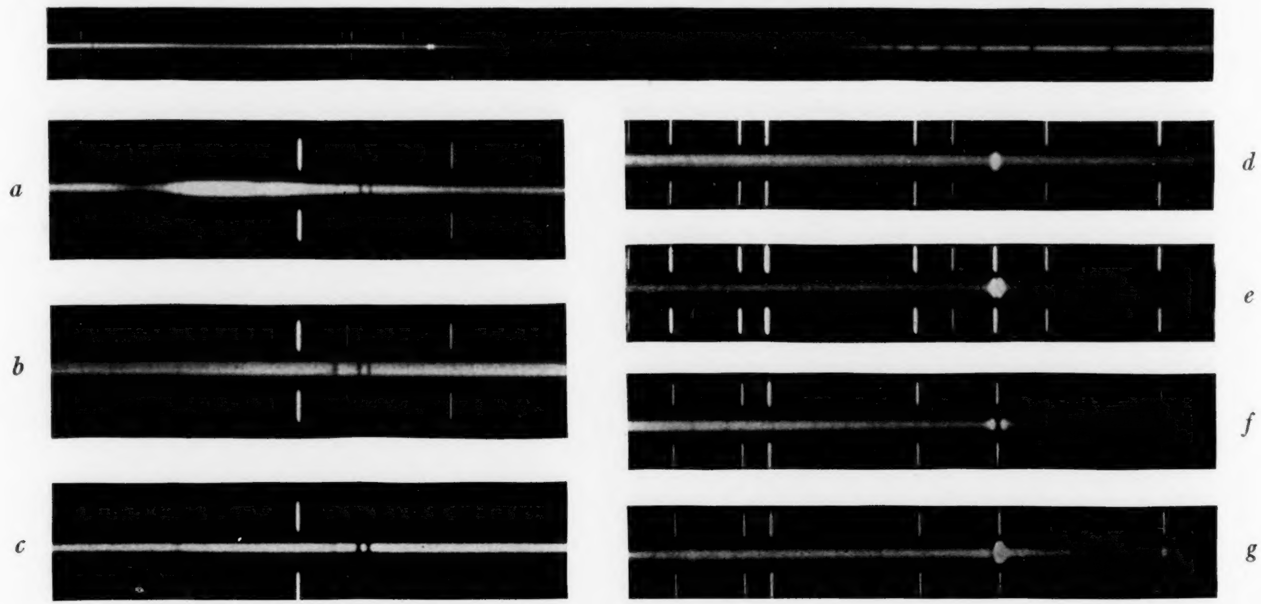
"The bases of the interchangeable cameras are made with a bevel which fits into two gibs on the main casting; one of the gibs is fixed and the other is clamped by a series of screws driven by miter gears, operated by a single shaft. The camera slips into position between the gibs, its location being defined by a stop pin. An automatic latch prevents the camera from sliding out of the spectrograph, should the clamping gib become loosened in any manner, but may be released by a push rod when the observer is ready to remove the camera.

"The supporting frame for the spectrograph is constructed of Shelby seamless steel tubes and aluminum alloy angle castings. It has the general form of a pyramid with a rectangular base, a type of support which is inherently stable and gives maximum stiffness for its weight. Each of the four corner castings at the base is provided with lugs (1-inch special cap screws) for fastening to the telescope.

"The supporting frame also carries the comparison apparatus, the heating coils, motor, and circulating fan for the temperature control, and the guiding telescope for keeping the star's image on the slit.

"A turret device makes it possible to swing into place for the comparison spectrum, one at a time, Hilger low-voltage (200 volts) vacuum tubes containing neon, argon, or helium. Also mounted on this device is a prism for reflecting a comparison arc of iron or titanium into the slit. When changing to the various comparison light sources the electrical contacts are made automatically and the control is by rods with knobs placed near the eyepiece of the guiding telescope and convenient to the observer."

PLATE VIII



Top ζ Tauri, H.D. 37202; mag. 3.0; spectrum B3e; plate G 50, 1925 Jan. 3

a) H.D. 193793, mag. 6.8; spectrum Oa; plate G 384, 1930 July 10

b) H.D. 225094, mag. 6.3; spectrum B3sea; plate G 402, 1930 Aug. 9

c) H.D. 223960, mag. 7.0; spectrum B9sea; plate G 274, 1929 Oct. 10

d) c Persei, H.D. 25940, mag. 4.0; spectrum B3e; plate G 112, 1926 Jan. 27

e) H.D. 50138, mag. 6.6; spectrum B8ev; plate G 302, 1930 Feb. 15

f) H.D. 142983, mag 4.7; spectrum A3sea; plate G 386, 1930 July 11

g) P Cygni, H.D. 193237, mag. 4.9; spectrum Beq; plate G 187, 1928 Aug. 1

Much credit for the excellent performance of this instrument goes to Mr. Nichols and to the Observatory shop, where the instrument was constructed under the supervision of Mr. A. F. Ayers. Flexure seems to have been practically eliminated, and no displacement of the lines is noticeable even on the longest exposures, of which many have exceeded three hours and a few have extended to six hours.

A number of observations already made with this instrument indicate the types of investigation in which it promises to prove useful. It is convenient to consider separately the region covered by ordinary panchromatic plates extending into the red as far as, say, B λ 6870 and the region of longer wave-length for which special emulsions are required.

In the first region are many lines which merit more attention than has yet been devoted to them. These include the detached sodium lines in stars of early type; *He*, λ 5876 D3 and λ 6678; *Si* II, $\lambda\lambda$ 6347, 6371; *C* II, $\lambda\lambda$ 6578, 6582; the forbidden lines of *N* II, $\lambda\lambda$ 6548, 6584; the forbidden lines of *O* I, $\lambda\lambda$ 6300, 6363; several *Ca* I lines whose intensity in stars of late type depends on absolute magnitude;[1] and the emission $H\alpha$ line in Be spectra. This list, of course, is far from complete.

A problem to which the spectrograph is adapted and which was, in fact, particularly in mind in planning this instrument is that of the abnormally strong sodium D lines in spectra of early type. In many stars these are "detached," i.e., arise in material not bound to the star, and may be interstellar, as the detached H and K lines are now generally believed to be, but in other stars their status is still somewhat uncertain. (See Plate VIII *a*, *b*, *c*.)

The only detached lines so far known are the H and K lines of ionized calcium and the D lines of neutral sodium; it would be valuable to compare their intensities as accurately as possible. The grating offers the interesting possibility of photographing both pairs of lines on the same plate—the D lines in the first order, H and K in the second order. The spectrogram of ζ Tauri (Plate VIII) illustrates this possibility.

[1] Cora G. Burwell, *Publications of the Astronomical Society of the Pacific*, **42**, 351, 1930.

The star H.D. 190073,[1] having *bright* sodium lines, is an interesting object for detailed investigation.

The grating should be useful for observing red stars in which the intensities of the sodium lines seem to show an inverse correlation with the intensities of titanium oxide bands.

In Be spectra considerable interest lies in the behavior of the $H\alpha$ line. Its bright components are always more intense than those of the other Balmer lines and may be extremely strong compared to the adjacent continuous spectrum. It will be important to study the structure of this line in relation to that of the other hydrogen lines. Several different types have been photographed (see Plate VIII *d, e, f, g*). All the observations of the $H\alpha$ line have been with the 10-inch camera, but higher dispersion could be used to advantage for certain stars.

Mr. Sanford has employed this instrument in his investigation of the velocities of N-type stars and has kindly prepared the following statement of his experience with it:

"Well-exposed spectrograms of N stars as faint as the ninth visual magnitude have been obtained in fair seeing with exposures which do not exceed two hours. The probable error of the radial velocity from a single plate appears not to exceed ± 5 km/sec. Exposures with a one-prism spectrograph in the blue-violet region on such stars, especially for the later subdivisions, would be hopelessly long. This equipment has increased by nearly 200 per cent the number of radial velocities for class N stars."

On prismatic spectrograms the small dispersion in the red makes this part of the spectrum poorly adapted to the determination of radial velocities. With equal dispersion, however, the longer wave-lengths enjoy the advantage of a larger linear displacement for a given velocity: at $H\alpha$, for example, it is 1.5 times as great as at $H\gamma$.

Spectrograms of typical stars of various types taken for miscellaneous purposes have been measured by Miss Burwell. Her results indicate the accuracy with which measurements of wave-length can be made in this part of the spectrum with low dispersion (66 A per millimeter). If higher accuracy is desired, it can readily be obtained

[1] *Science*, **72**, 407, 1930.

by using a longer camera; for stars brighter than, say, magnitude 6.0 it is feasible to double the linear dispersion. Table I and the following discussion are by Miss Burwell.

TABLE I

RADIAL VELOCITIES FROM GRATING SPECTROGRAMS

(Region, λλ 5852–6717; dispersion, 66 A per mm)

Star	R.A. 1900	Dec. 1900	Mag.	Sp.	Date	Obs. Vel.	No. Lines	Adopted Vel.	Obs. − Ad.
						km/sec.		km/sec.	
α Ceti	2^h57^m1	+ 3°42′	2.8	M2	1930 Feb. 15	−23.5	21	−25.3	+1.8
ρ Persei	2 58.8	+38 27	Var.	M4	1925 Jan. 2	+25.5	7	+28.2	−2.7
ε Eridani	3 28.2	− 9 48	3.8	dK0	1930 Feb. 14	+18.3	22	+16.0	+2.3
ζ Aurigae	4 55.5	+40 56	3.9	K0	1924 Oct. 4	+27.7	24	(+10.7)	....
51 Geminorum	7 7.6	+16 20	5.3	M4	1930 Apr. 19	−19.9	14	−10.0	−9.9
κ Geminorum	7 38.4	+24 38	3.7	G5	1925 Jan. 2	+11.6	27	+20.4	−8.8
β Geminorum	7 39.2	+28 16	1.2	K0	1930 Apr. 19	+ 9.7	23	+ 3.6	+6.1
β Cancri	8 11.1	+ 9 30	3.8	K2	1925 Jan. 2	+18.1	32	+22.4	−4.3
40α Lyncis	9 15.0	+34 49	3.3	M0	1930 Apr. 18	+41.6	27	+37.9	+3.7
40α Lyncis	....	....	......	......	18	+36.1	21	+37.9	−1.8
α Ursae Majoris	10 57.6	+62 17	2.0	K0	1930 Feb. 15	−11.8	16	− 9	....
Lal 21185	10 57.9	+36 38	7.6	dM2	14	−87.4	14	−87*	0
61 Ursae Majoris	11 35.7	+34 46	5.5	dG5	14	− 5.6	12	− 5.0	−0.6
β Virginis	11 45.5	+ 2 20	3.8	F8	1925 Jan. 2	+ 3.5	14	+ 4.9	−1.4
8β Canum Venaticorum	12 29.0	+41 54	4.3	dG0	1930 Feb. 15	+11.7	11	+ 6.1	+5.6
α Boötis	14 11.1	+19 42	0.2	K0	1930 Apr. 17	0.0	21	− 5.4	+5.4
α Boötis	....	....	......	......	17	− 3.0	23	− 5.4	+2.4
θ Draconis	16 0.0	+58 50	4.1	F8	Feb. 15	+ 6.0	15	(− 8.5)	....
α Scorpii	16 23.3	−26 13	1.2	M1	Apr. 18	− 8.6	9	(− 3.0)	....
α Scorpii	....	....	......	......	18	− 7.3	28	(− 3.0)	....
α Herculis	17 10.1	+14 30	3.5	M5	1930 Apr. 16	−39.3	14	−32.6	−6.7
70 Ophiuchi A	18 0.4	+ 2 31	4.1	dK0	July 10	+ 0.4	27	(− 7.2)	....
70 Ophiuchi A	....	....	......	......	10	− 2.7	20	(− 7.2)	....
61 Cygni A	21 2.4	+38 15	5.6	dK7	Apr. 17	−67.8	17	−65.5*	−2.3
Boss 5481	21 16.5	+58 13	5.8	M1ep	Sept. 12	−19.6	38	−21.1*	+1.5
Boss 5650	21 53.8	+63 9	5.4	M2ep	1930 Sept. 12	−27.9	24	(−19)*	....
20 Pegasi	21 56.2	+12 38	5.7	F2	12	+ 3.4	15	+ 6.5*	....
Sky	....	....	......	G0	1929 Oct. 12	− 0.1	10	− 0.2	+0.1
Sky	....	....	......	......	1930 Apr. 18	− 0.8	9	+ 0.7	−1.5
Sky	....	....	......	......	18	+ 5.0	12	+ 0.7	+4.3

* Mt. Wilson value. See *Mt. Wilson Contr.*, No. 79; *Astrophysical Journal*, **39**, 283, 1914; also *Mt. Wilson Contr.*, No. 105; *Astrophysical Journal*, **42**, 411, 1915; and *Mt. Wilson Contr.*, No. 258; *Astrophysical Journal*, **57**, 31, 1923. Adopted velocities not starred are from *Publications of the Lick Observatory*, **16**, 1928. Velocities known to be variable are given in parentheses.

"The velocities in the seventh column of Table I are the means of at least two measures on each exposure. Results from different exposures on the same plate are listed separately.

"The wave-lengths adopted for the stellar lines were taken from the *Revision of Rowland's Table*.[1] In the case of blends, which with

[1] St. John, Moore, Ware, Adams, Babcock, *Revision of Rowland's Preliminary Table of Solar Spectrum Wave-Lengths, etc.; Carnegie Institution of Washington Publication*, No. 396; *Papers of the Mount Wilson Observatory*, **3**, 1928.

a dispersion of 66 A per millimeter are numerous, the components were weighted according to their intensities. For stars of types K and M, the spot intensities were used; for the earlier types, those of the disk.

"Probable errors are approximately ± 5.0 km/sec. for lines of average quality and ± 1.0 km/sec. for good plates on which twenty or thirty lines were measured. The accidental errors of measurement are therefore as small as could be expected. In a long radial-velocity program, systematic errors could probably be decreased, and this might lead to a somewhat closer agreement with the standard velocities. The residuals shown in Table I are, however, probably not unduly large in view of the small number of plates and the incidental nature of the determinations."

In the region beyond B a few observations of stellar spectra have previously been made by V. M. Slipher,[1] J. Bosler,[2] P. W. Merrill,[3] and W. H. Wright.[4] These observers used low-dispersion prismatic spectrographs. I find no record of prior observations with gratings.

It is planned to use the Mount Wilson grating spectrograph for a reconnaissance of the various types of stellar spectra in the region λλ 6870–8700. An effort may be made to reach still longer wavelengths in the spectra of a few very bright stars. The numerous lines introduced by the earth's atmosphere between λ 7600 and λ 8350 interfere with the investigation of stellar lines in this region and may detract from its general usefulness. On the other hand, the terrestrial lines (always in the same positions) may serve as standards for the determination of displacements of stellar lines.

The most interesting photograph so far obtained of the region between the Fraunhofer lines B and A is perhaps that of the N-type star, Y Canum Venaticorum (Plate IX). With the exception of the cyanogen bands λλ 6910, 6925, 6943,[5] the features lack conclusive

[1] *Astrophysical Journal*, **25**, 235, 1907; *Encyclopaedia Britannica* (11th ed.), **21**, 717, 1910–1911. His work on the spectra of planets has been extensive: *Lowell Observatory Bulletins*, **1**, 231, 1903–1911; *Popular Astronomy*, **37**, 140, 1929.

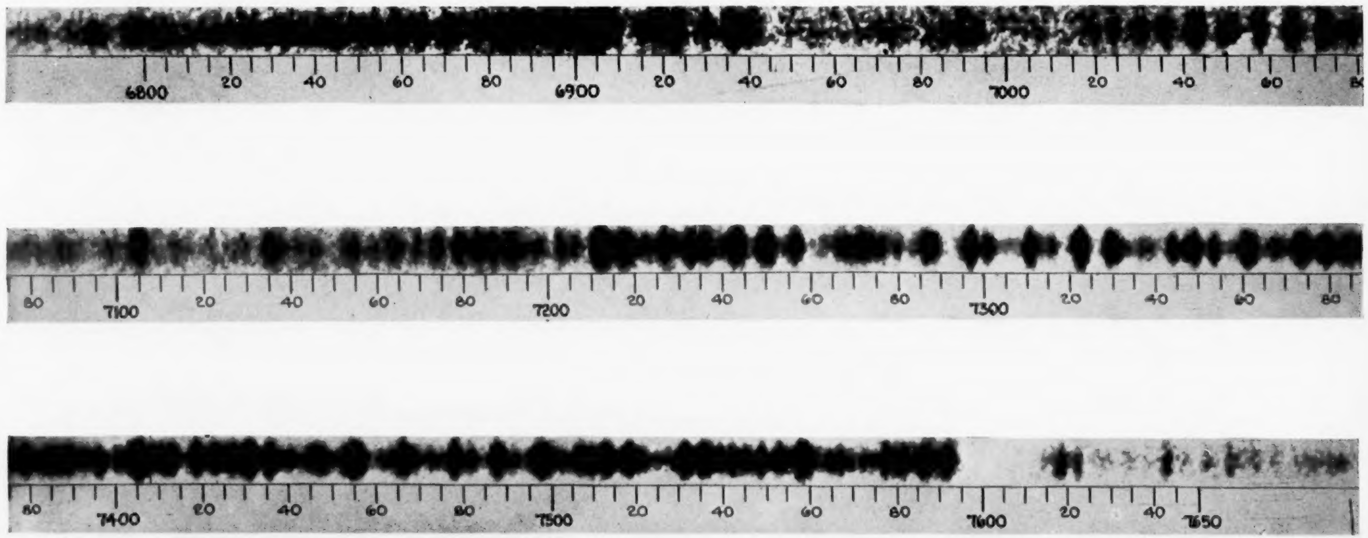
[2] *Comptes rendus*, **160**, 124, 1915.

[3] *Scientific Papers of the Bureau of Standards*, **14** (No. 318), 487, 1918.

[4] *Publications of the Astronomical Society of the Pacific*, **32**, 63, 1920.

[5] A. S. King, *ibid.*, **38**, 173, 1926.

PLATE IX



Y Canum Venaticorum, H.D. 110914; mag. 4.8–6.0; spectrum Nb; plate G 159, 1928 June 30.

Emulsion "Extreme Red Sensitive" prepared by the Research Laboratory of the Eastman Kodak Co., hypersensitized at Mount Wilson by an ammonia bath.

identification, although many possible coincidences have been noted by Dr. C. D. Shane and the writer. It is probable that a number of other bands are involved, but the laboratory data are not sufficient to make their identifications obvious. Heads of absorption bands seem to appear at λ 7210 and at other points whose wave-lengths can be read from the illustration. At λ 7105 is a maximum which may be a narrow section of the continuous spectrum between two bands facing in opposite directions, although this explanation involves a rather improbable coincidence. It may be an emission line. Several groups of alternating maxima and minima, particularly those near λ 7050 and λ 7180, resemble coarse band structures.

An important nebular line λ 7325, really a close multiplet, has been photographed with the grating spectrograph,[1] and its structure is found to confirm I. S. Bowen's identification[2] of it with *O* II. This also makes more certain his identification of the well-known ultraviolet doublet $\lambda\lambda$ 3726–3729 with *O* II. Although a few observations of the oxygen triplet $\lambda\lambda$ 7772–7774–7775 in stars of early type were made several years ago,[3] a more extensive study is desirable.

A few experimental spectrograms on neocyanin plates have shown the region from λ 8350 to λ 8700 to be of considerable interest, especially in the cooler stars. It is comparatively free from atmospheric lines and titanium bands and contains, in addition to the great *Ca* II D–P triplet, $\lambda\lambda$ 8498, 8542, 8662, numerous low excitation lines of neutral titanium and iron.

The infra-red calcium lines arise from a low metastable D term and thus to a certain extent have in absorption the properties of ultimate lines. We may expect them to be strong in all stars except the hottest and the coolest. The observations, as far as they go, bear this out, for the lines are weak in α Lyrae and α Canis Majoris; very strong in the sun, α Boötis, and α Scorpii; of moderate strength in α Herculis; and weak in o Ceti.

A group of titanium lines near λ 8400 is conspicuous in M-type spectra. The strong pair $\lambda\lambda$ 8434–8435 is outstanding in the spectra of α Herculis and o Ceti. This shows that the oxidation of titanium atoms evidenced by the strong oxide bands is not at all complete.

[1] *Ibid.*, **40**, 254, 1928.

[2] *Ibid.*, **39**, 295, 1927.

[3] *Ibid.*, **37**, 272, 1925.

A strongly exposed plate of *o* Ceti, mag. 3, phase 9 days after maximum, was obtained on August 31, 1928. Several lines are seen beyond *Ca* λ 8662, the extreme one having a wave-length of approximately 8704 A. Another plate having satisfactory density from

TABLE II

ABSORPTION LINES IDENTIFIED IN THE SPECTRUM OF *o* CETI

I.A. (Lab.)	E.P.	I.A. (Lab.)	E.P.
8364.18 *Ti*	0.83	8498.00 *Ca* II	1.68
(8365.61 *Fe*)	....	8518.20 *Ti*	1.87
8377.83 *Ti*	0.82	8542.15 *Ca* II	1.69
8382.61 *Ti*	0.81	8662.11 *Ca* II	1.68
8387.74 *Fe*	2.17	(8674.69 } *Fe*)	2.82
8396.85 *Ti*	0.81	8675.33 } *Ti*	1.06
8412.34 *Ti*	0.82	8682.93 *Ti*	1.05
8426.46 *Ti*	0.82	8688.58 *Fe*	2.17
8434.89 *Ti*	0.84	8692.29 *Ti*	1.04
8435.65 *Ti*	0.83		
8468.35 } *Fe*	2.21		
8468.45 } *Ti*	1.88		

the Fraunhofer line A to λ 8550 was obtained on the following night in 132 minutes. Eight lines, mostly titanium, from λ 8365 to λ 8436 give a radial velocity of +64 km/sec., in close agreement with the known velocity at maximum light.[1] The lines in Table II have been identified on these two plates of *o* Ceti.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
May 1931

[1] Joy, *Mt. Wilson Contr.*, No. 311; *Astrophysical Journal*, **63**, 281, 1926.

ORBITAL ELEMENTS OF THE SPECTROSCOPIC BINARIES H.D. 73619, 75767, 206546, AND 214686[1]

By ROSCOE F. SANFORD

ABSTRACT

Orbital elements have been derived from Mount Wilson spectrograms *for the four stars* H.D. 73619, 75767, 206546, and 214686. For each star a diagram illustrates the variations in radial velocity.

H.D. 73619, one of the brighter members of the Praesepe cluster, has components of about the same spectral class, magnitude, and mass, rotating in an elliptic orbit of eccentricity 0.2 with a period of 12^d9117. The velocity of the center of mass, +32.1 km/sec., agrees very closely with the mean velocity of more than twenty other stars in the cluster.

H.D. 75767, a dwarf star of spectral class G1, shows only the spectral lines of the primary. The orbit is slightly elliptic (eccentricity 0.1); the period is 10^d2504.

H.D. 206546 is a spectroscopic binary whose components are alike in magnitude, spectral type, and mass. The orbit is sensibly circular; the period is 6^d3702.

H.D. 214686 also has similar components. In this case the orbit has an eccentricity of 0.38 and is so oriented that the component lines are resolved at ascending, but not at descending, node The period is 21^d6997.

Only the first of the four spectroscopic binaries here considered (Table I) has previously been announced as a binary.[2] The plates

TABLE I

H.D.	Boss P.G.C.	B.D.	α 1900	δ 1900	H.D. Mag.	H.D. Sp. Class
73619	....	+20°2153	8^h34^m2	+19°54′	7.2	A0
75767	....	+ 8 2134	8 46.8	+ 8 26	6.6	G0
206546	5575	−20 6270	21 37.8	−20 04	6.2	A3
214686	5846	−10 5966	22 34.8	− 9 53	6.7	G0

were obtained with one-prism spectrographs fitted with cameras of 18 inches focal length which give at $H\gamma$ a dispersion of about 37 A per millimeter. Plates whose numbers are preceded by C were taken with the 100-inch reflector; those with the prefix γ refer to the 60-inch reflector.

H.D. 73619

This star is a member of the Praesepe cluster. The last of three spectrograms of the star obtained in 1923 showed two sets of lines

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 433.

[2] *Publications of the Astronomical Society of the Pacific*, **36**, 137, 1924.

belonging to the components of a spectroscopic binary. The separation corresponded to a difference of velocity of 160 km/sec. Obser-

TABLE II

RADIAL VELOCITIES OF H.D. 73619

Plate No.	Date	G.M.T.	Phase	Velocities in Km/Sec.		
				Prim.	Blended	Sec.
C 2085	1923 Jan. 6	22^h09^m	3^d658	....	+32	....
γ 11665	Mar. 26	17 02	10.798	....	+31	....
11682	28	17 11	12.804	−53	....	+113
14048	1926 Feb. 23	20 37	4.276	....	+31	....
14054	24	20 06	5.255	+74	....	− 14
14057	25	19 38	6.235	+82	....	− 15
C 4159	1927 Jan. 9	21 38	1.526	−30	....	+ 83
γ 14863	Mar. 17	15 41	3.720	....	+36	....
14866	17	19 21	3.872	....	+33	....
15456	Dec. 31	18 28	8.778	+84	....	− 8
15461	1928 Jan. 1	18 13	9.768	....	+25	....
15469	2	23 12	10.976	....	+30	....
C 4608	3	22 32	11.948	−20	....	+ 86
γ 15494	6	00 10	1.104	−37	....	+ 95
16366	Dec. 28	22 25	10.422	....	+40	....
16376	30	20 59	12.355	−36	....	+ 96
16381	31	19 27	0.379	−47	....	+105
17210	1930 Feb. 6	22 37	2.249	....	+26	....
17259	14	21 24	10.199	....	+40	....
17265	15	20 25	11.158	....	+44	....
17275	17	16 49	0.096	−49	....	+105
C 5438	1930 Apr. 15	17 39	5.400	+85	....	− 13
γ 17401	16	17 06	6.461	+71	....	− 16
17415	19	16 20	9.429	+53	....	− 10
C 5442	May 11	16 30	5.613	+82	....	− 9
γ 17447	12	16 14	6.601	+82	....	− 10
17457	13	16 29	7.612	+70	....	− 29
17462	14	16 36	8.617	+77	....	− 18
C 5611	Nov. 5	01 11	2.210	− 2	....	+ 53
γ 17979	Dec. 12	01 35	0.492	−34	....	+114
17983	12	23 27	1.403	−26	....	+ 90
18033	1931 Jan. 3	23 51	10.508	....	+34	....
18048	29	19 20	10.497	....	+29	....
..18054	Feb. 1	20 18	0.625	−31	....	+107
18062	25	21 55	11.780	−20	....	+ 88
18068	27	21 00	0.831	−42	....	+104
18077	Mar. 1	18 10	2.713	....	+32	....
18084	2	17 00	3.664	....	+36	....
18093	3	18 56	4.745	+72	....	− 1
18098	4	18 16	5.717	+81	....	− 10
18101	6	19 59	7.789	+88	....	− 13
18106	7	18 00	8.706	+74	....	− 14
18116	8	18 20	9.720	+66	....	+ 2
18123	9	16 23	10.639	....	+24	....
18132	10	17 5	11.668	−11	....	+ 84
18165	31	16 10	6.806	+72	....	− 20

vations were continued as opportunity permitted until the end of the 1930–1931 observing season. The forty-six spectrograms thus accumulated give a period of $12^{d}.9117$, which satisfactorily represents all the velocities. These plates are listed in Table II along with the data necessary for the determination of the orbit.

The components have approximately the same brightness and spectral type. The type derived from spectrograms on which the two spectra are superposed is F1s. Most of the lines are rather poor

TABLE III

ELEMENTS OF H.D. 73619

$P=12^{d}.9117$	$\gamma=+32.1$ km/sec.
$T=$ J.D. 2425250.803 G.M.T.	$m_1 \sin^3 i=1.386 \odot$
$\omega_1=168^{\circ}.2$	$m_2 \sin^3 i=1.354 \odot$
$\omega_2=348^{\circ}.2$	$\frac{m_2}{m_1}=0.98$
$e=0.2$	$a_1 \sin i=11,134,000$ km
$K_1=64.0$ km/sec.	$a_2 \sin i=11,395,000$ km
$K_2=65.6$ km/sec.	

and unsuitable for accurate measurement, especially when the separation of the two sets of lines is near the limit of resolution.

The velocity-curve shows that periastron is located near one node and apastron near the other. Since the spectral lines of the two components have a relatively wide separation near periastron, while at apastron they are resolved with difficulty, the relative weights of the measures at the two epochs show a marked difference. The adopted orbit was therefore obtained by trial-and-error adjustment of the elements derived by Russell's method.[1] The results are in Table III.

Figure 1 shows the velocity-curves given by these elements and the representation of the individual measures. Circles of 4 km/sec. radius indicate measures near periastron where the separation of the two components is largest. Measures of blended lines and of those difficult to resolve (near apastron) are represented by circles of 6 km/sec. radius. The agreement seems sufficient to justify the adoption of the elements given in Table III.

The values of $m \sin^3 i$ are plausible, provided the unknown in-

[1] *Astrophysical Journal*, **40**, 282, 1914.

clination does not differ greatly from 90°. The times of eclipse, if eclipses occur, would be given by

$$T = \text{J.D. } 2425238.24 \text{ and } 2425253.97 \text{ (G.M.T.)} + 12^{d}.9117E \ .$$

Simple considerations show, however, that i would probably have to be at least as great as 80°. I find no note of suspected variability for the star.

The velocity of the system in Table III may be checked by forming the mean of each pair of velocities obtained from the double-lined spectra. If the numbers of such velocities near periastron and

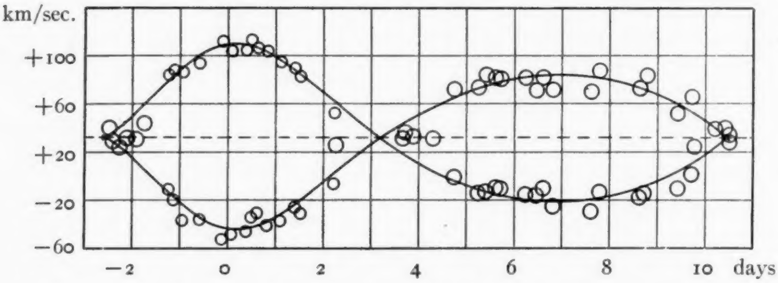


FIG. 1.—Velocity-curve for H.D. 73619. Small circles, observations near periastron where separation of components is largest; large circles, measures of blends and lines difficult to resolve.

apastron are approximately the same, the small differences between K_1 and K_2 will have no appreciable effect, and the mean of all should be a fair approximation to the velocity of the system. Further, since the mean of velocities from the spectrograms showing blended lines is negligibly affected by differences of intensity in the component lines, this mean furnishes a second check. A final value is afforded by the mean radial velocity obtained from twenty-two other known members of the Praesepe cluster. Table IV shows the four results. The first and last are probably entitled to most weight and indicate that on the basis of the wave-lengths used for the Mount Wilson reduction tables the velocity of the cluster lies between +32.1 and +32.4 km/sec.

The parallax of the Praesepe cluster is of the order of 0".007; the corresponding absolute magnitude is 2.2 for each component of the binary.

H.D. 75767

This star was placed on the Mount Wilson program for spectroscopic absolute magnitudes because of its large proper motion. Its spectral type was found to be dG1; absolute magnitude, +4.3. The spectrum includes many good metallic lines and should give radial velocities of considerable accuracy. The range shown by the first four spectrograms (1924–1925) made it highly probable that it was a spectroscopic binary. The data for thirty-seven spectrograms obtained between February 17, 1924, and April 27, 1929, are given in Table V. There is no evidence of a secondary spectrum.

TABLE IV

VELOCITY OF THE PRAESEPE CLUSTER

	$\gamma = +32.1$ km/sec.
Mean of double-lined spectrograms	= 32.8
Mean for blended spectra	= 33.4
Mean of the radial velocities of 22 other members of the Praesepe cluster	= +32.4

The period which gives the best grouping of the individual velocities is $10^{d}.2504$. The remaining elements, found by Russell's method, are in Table VI. An attempt at least-squares correction to these values was made by assuming P to be known and using the thirteen normals given in Table VII. Two of the five normal equations are, however, nearly identical, and corrections to ω and T cannot be determined independently. Since the corrections to all the elements are evidently small, no serious error can result from the use of the preliminary values of Table VI; these have therefore been adopted. No outstanding feature appears in the elements, in the mass function ($0.0154\odot$), or in $a_1 \sin i$ (3,436,000 km). The small eccentricity is consistent with what has been noted in other dwarf spectroscopic binaries. Figure 2 shows the velocity-curve given by the elements, with circles representing the normal places.

H.D. 206546

The first four spectrograms of this star showed only single lines and gave reasonably accordant radial velocities. The fifth spectrogram, however, showed unmistakably two sets of lines with a difference in velocity of 160 km/sec. which must be ascribed to relative

TABLE V

RADIAL VELOCITIES OF H.D. 75767

Plate No.	Date	G.M.T.	Phase	Vel.
			days	km/sec.
γ 12492	1924 Feb. 17	21^h39^m	8.930	+ 0.9
12556	Apr. 12	17 28	2.254	+11.8
12659	May 19	15 38	8.426	− 1.5
13146	1925 Jan. 2	23 50	1.007	+29.2
13948	Dec. 29	20 57	3.122	+18.3
13995	1926 Jan. 25	20 36	9.605	− 0.8
14004	26	19 39	0.316	+27.5
14015	27	22 14	1.423	+34.0
C 3676	Feb. 4	20 47	9.363	+ 7.6
3678	5	19 51	0.074	+17.6
γ 14046	23	17 53	7.741	−11.6
14055	24	21 21	8.886	+ 5.4
C 3715	26	20 20	0.593	+21.0
γ 14074	28	16 55	2.451	+18.9
14770	Dec. 20	0 34	9.757	+ 5.5
C 4160	1927 Jan. 9	22 59	10.190	+23.6
γ 14779	12	19 15	2.784	+19.8
14859	Mar. 16	19 3	4.273	− 6.0
14864	17	16 44	5.176	−15.7
14867	17	20 32	5.335	−14.1
15369	Nov. 3	0 33	9.992	+14.7
15432	Dec. 7	0 49	3.002	+19.4
15457	31	19 51	7.294	−20.2
15470	1928 Jan. 3	0 12	9.474	+ 8.2
15498	6	22 09	3.139	+10.2
15516	9	21 55	6.129	−16.2
15591	Feb. 8	17 21	5.188	−18.3
16367	Dec. 28	23 34	1.433	+31.9
16371	29	21 53	2.363	+26.6
16377	30	22 26	3.386	+ 8.1
16382	31	21 25	4.344	+ 0.1
16390	1929 Jan. 1	22 37	5.393	−12.3
C 5155	Mar. 29	16 55	10.151	+27.3
γ 16507	Apr. 1	18 18	2.959	+16.4
16541	23	16 10	4.370	− 1.8
16547	24	17 00	5.404	−12.8
16551	27	16 05	8.366	− 4.6

TABLE VI

T = J.D. 2424891.018 G.M.T.

$\omega = 314^\circ$

$e = 0.1$

$K =$ 24.5 km/sec.

$\gamma = +3.5$ km/sec.

motion of the components of a spectroscopic binary. The differences in spectral type and line intensity are negligible. Data for thirty-four spectrograms which define the orbit with fair precision appear in Table VIII.

TABLE VII

NORMAL PLACES OF H.D. 75767

No.	Phase	Vel.	O−C	Wt.
	days	km/sec.	km/sec.	
1	0.328	+22.0	−4.2	2.5
2	1.288	+31.7	+2.1	3.0
3	2.609	+16.3	−2.5	2.5
4	2.903	+17.0	+1.9	3.0
5	2.975	+16.5	+2.4	3.0
6	4.329	− 2.6	+0.8	2.0
7	5.233	−16.0	−3.5	3.0
8	5.642	−13.8	+1.8	3.0
9	7.518	−15.9	+0.6	2.0
10	8.987	− 0.5	−2.0	3.0
11	9.124	+ 6.5	+3.1	1.5
12	9.199	+ 3.0	−2.2	2.5
13	10.111	+21.9	+1.4	3.0

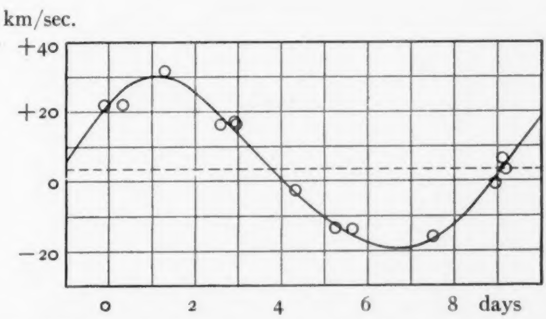


FIG. 2.—Velocity-curve of H.D. 75767. Circles represent the normal places of Table VII.

A period of $6^{d}.3702$ gives the most satisfactory grouping of the observations and was adopted as final. The remaining elements, which were derived by Russell's method and some subsequent adjustment, are those of circular orbits. Phases were reckoned from the time of maximum negative velocity for the primary star. Corrections to γ, K_1, K_2, and T were obtained from the combined data for the two components by the method of least squares. Table IX

TABLE VIII

RADIAL VELOCITIES OF H.D. 206546

PLATE NO.	DATE	G.M.T.	PHASE	VELOCITIES IN KM/SEC. Prim.	Blended	Sec.
			days			
γ 12161	1923 Oct. 1	$16^h 11^m$	4.496	....	−24	....
12222	24	15 03	1.968	....	46	....
12931	1924 Sept. 9	18 15	4.593	....	41	....
13582	1925 July 31	21 29	4.849	....	28	....
13678	Aug. 30	19 47	2.927	+ 51	....	−109
16024	1928 July 28	21 25	2.177	+ 6	....	− 91
16113	Aug. 26	18 49	5.587	− 72	....	+ 48
C 4949	27	17 40	0.170	−108	....	+ 70
4956	28	18 02	1.185	− 84	....	+ 19
γ 16128	29	19 33	2.249	+ 20	....	− 94
16189	Sept. 27	17 47	5.694	− 92	....	+ 42
16195	28	15 5	0.211	−100	....	+ 53
16204	29	17 53	1.328	....	23	....
C 5008	30	19 32	2.397	+ 28	....	− 94
5011	Oct. 1	14 48	3.200	+ 60	....	−119
γ 16233	4	16 16	6.261	−104	....	+ 64
C 5052	24	16 55	0.807	− 96	....	+ 35
γ 16903	1929 Sept. 12	17 28	5.322	− 74	....	+ 9
16912	14	18 43	1.004	− 83	....	+ 40
C 5342	Oct. 19	17 38	4.107	+ 22	....	− 93
5347	20	15 50	5.033	....	37	....
γ 17024	21	16 55	6.078	−103	....	+ 55
17031	22	15 51	0.663	− 91	....	+ 44
17042	23	16 31	1.691	....	15	....
17496	1930 June 6	23 17	5.017	....	27	....
17563	July 6	23 14	3.164	+ 64	....	−105
17675	Aug. 13	19 28	2.786	+ 51	....	−105
17683	14	19 51	3.802	+ 44	....	− 89
17689	15	20 38	4.835	....	−28	....
C 5607	Nov. 4	15 5	2.791	+ 48	....	−102
γ 17861	5	15 9	3.794	+ 43	....	− 92
17899	29	14 3	2.267	+ 29	....	− 85
17908	30	13 40	3.251	+ 54	....	−118

TABLE IX

ELEMENTS OF H.D. 206546

Preliminary	Corrections	Adopted
P	....	$6^d.3702$
T = J.D. 2425486.7	−0.133	5486.567 G.M.T.
K_1 = 83.2	−1.1	82.1 km/sec.
K_2 = 88.4	−2.1	86.3 km/sec.
γ = −26.4	+0.9	−25.5 km/sec.
$m_1 \sin^3 i$	....	1.618 ⊙
$m_2 \sin^3 i$	....	1.540 ⊙
$a_1 \sin i$	....	7,191,000 km
$a_2 \sin i$	....	7,559,000 km

gives the preliminary and corrected elements, and the functions of mass and mean distance.

Figure 3 is the radial-velocity diagram, the smaller circles representing the velocities from spectrograms with well-separated double lines and the larger circles those with double lines either difficult of resolution or blended.

The spectral class and absolute magnitude determined at Mount Wilson are A6n and 1.3, respectively. The absolute magnitude of each of the two equal components is therefore 2.0. The better defi-

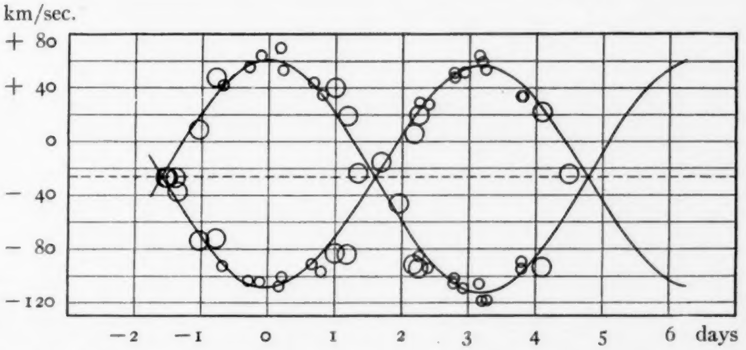


FIG. 3.—Velocity-curve of H.D. 206546. Small circles, measures of well-separated double lines; large circles, lines difficult of resolution and blends.

nition of slit spectrograms and the possibility of selecting those with component lines superposed has led to a somewhat later type than that derived from the Harvard objective-prism spectrograms.

H.D. 214686

The second spectrogram of this star showed it to be a spectroscopic binary with components nearly alike in both magnitude and spectrum. Observations for the determination of its orbit were disappointing for some time, however, because the period of a few days indicated by some runs of observations did not appear to be substantiated by others. More spectrograms than usual were therefore obtained before it became clear that the period is not very long and that the apparent inconsistencies arise from the fact that periastron is near one node and apastron near the other. This permits easy resolution of the two components at the one phase and practically

TABLE X

Radial Velocities of H.D. 214686

Plate No.	Date	G.M.T.	Phase	Velocities in Km/Sec.		
				Prim.	Blended	Sec.
			days			
γ 15209	1927 Aug. 18	21^h48^m	4.210	− 68	....	− 8
15216	Sept. 3	20 53	20.172	107	....	+36
15224	4	21 07	21.182	119	....	+36
15231	5	20 10	0.442	94	....	+14
C 4407	6	19 10	1.401	....	−20	....
γ 15247	9	20 06	4.440	....	51	....
15253	10	19 23	5.410	....	36	....
15265	14	19 35	9.418	....	45	....
15270	15	19 10	10.401	....	23	....
C 4435	Oct. 4	18 06	7.657	....	66	....
4441	5	16 39	8.597	....	42	....
γ 15281	9	15 41	12.557	....	44	....
15284	9	19 38	12.721	....	40	....
15292	10	16 17	13.579	....	52	....
15300	11	16 22	14.585	....	45	....
15308	12	19 10	15.702	....	46	....
15312	13	15 07	16.533	....	38	....
15315	13	19 27	16.713	....	39	....
15320	15	17 04	18.614	79	....	+12
15326	16	18 13	19.662	102	....	+24
15333	17	18 40	20.681	118	....	+33
15335	18	15 27	21.546	109	....	+35
15346	19	16 26	0.888	74	....	+ 8
15364	Nov. 2	16 00	14.870	....	39	....
15370	3	15 50	15.863	....	44	....
C 4525	6	17 54	18.949	91	....	+10
γ 15400	15	16 16	6.181	....	38	....
C 4568	Dec. 7	14 59	6.428	....	41	....
γ 15903	1928 June 21	23 17	8.476	....	30	....
15930	29	23 5	16.468	....	40	....
15935	30	23 29	17.485	....	25	....
15941	July 3	23 19	20.478	102	....	+46
15945	4	23 05	21.468	119	....	+35
15951	6	23 06	1.770	....	42	....
15969	10	22 39	5.751	....	31	....
16020	27	22 45	1.055	....	17	....
16025	28	22 56	2.063	....	43	....
16114	Aug. 26	20 38	9.267	71	....	+ 4
C 4950	27	18 20	10.171	....	38	....
4952	27	23 26	10.383	....	32	....
4957	28	18 20	11.171	....	42	....
γ 16129	29	20 55	12 279	....	39	....
16188	Sept. 27	16 44	19.404	101	....	+29
16205	29	19 34	21.522	110	....	+29
C 5006	30	14 57	0.631	....	44	....
5009	30	20 28	0.861	....	−34	....
γ 16825	1929 Aug. 19	20 51	20.081	106	....	+28
16834	20	21 33	21.110	−115	....	+44

TABLE X—*Continued*

Plate No.	Date	G.M.T.	Phase	Velocities in Km/Sec.		
				Prim.	Blended	Sec.
			days			
C 5292	1929 Sept. 10	21^h16^m	20.398	−113	....	+46
5295	11	17 30	21.241	103	....	+36
γ 16904	12	18 53	0.600	91	....	+11
16913	14	20 29	2.667	....	−40	....
C 5343	1929 Oct. 19	18 47	15.896	....	−36	....
γ 17493	1930 June 5	23 10	6.381	....	−36	....
C 5517	1930 Aug. 13	19 50	10.143	68	....	+ 8
5608	Nov. 4	16 36	6.210	− 83	....	−17

prevents it in the other. The possibility that a period of about one day is involved has not been overlooked. Pairs of spectrograms taken on four different nights give radial velocities difficult to reconcile with such a period.

Table X gives the data for the sixty-one suitable spectrograms obtained in the years 1927–1930.

A period of $21^{d}.675$ provided a consistent grouping of the observations such that all with easily measurable double lines fall in one phase interval, while those with blended spectra are distributed as would be expected from the breadth of the blends on the assumption that near apastron the dispersion was insufficient to resolve them. Observations which define the velocity-curve so imperfectly necessarily give elements inferior to those obtainable from spectra showing double lines at both nodes. Fairly satisfactory preliminary results were obtained, partly by trial and partly by Russell's method. A least-squares solution was then used for correction. This was based upon the residuals given by the spectrograms which show double lines taken near periastron and could be reliably measured As was to be expected, the corrections to γ could not be determined independently of those to K_1 and K_2. Nevertheless, Σv^2 for the corrected elements was much less than for the preliminary elements; but Σv was not zero. The new values of ω, e, T, and P were adopted, and further improvement in the representation of the observations was sought by assuming that the mean of all the velocities from

spectrograms with blended spectra is the best available value of γ, the velocity of the center of mass. The values of K_1 and K_2 were then adjusted to give $\Sigma v = 0$ for the spectrograms used in the least-

TABLE XI

ELEMENTS OF H.D. 214686

Preliminary	Corrections	Adopted
P = 21^{d}675	+ 0^{d}0247	21^{d}6997
T = J.D. 2425172.659	+ 0.138	5172.797 G.M.T.
ω_1 = 194°0	+19°1	213°1
ω_2		33.1
e = 0.37	+ 0.01	0.38
K_1 = 56.7	− 0.2	56.5 km/sec.
K_2 = 57.3	+ 3.0	60.3 km/sec.
γ = − 37.7	− 1.6	−39.3 km/sec.
$m_1 \sin^3 i$		1.468 ☉
$m_2 \sin^3 i$		1.376 ☉
$a_1 \sin i$		15,599,000 km
$a_2 \sin i$		15,648,000 km

squares solution. The preliminary and the adopted elements are in Table XI. The final Σv^2 is only 38 per cent of its value for the preliminary elements.

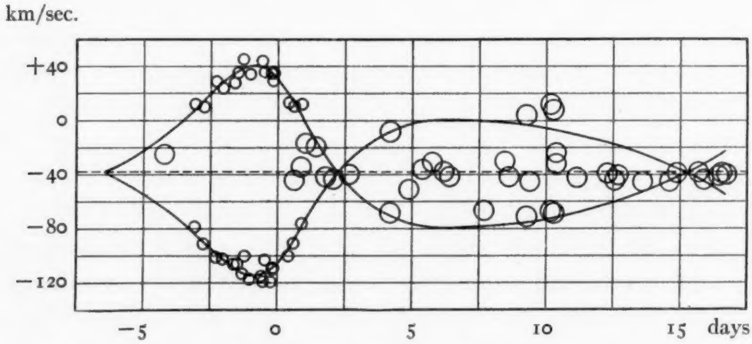


FIG. 4.—Velocity-curve of H.D. 214686. Small circles indicate the more accurate results obtained from clearly resolved spectra.

Figure 4 shows the velocity-curves defined by the corrected elements and the radial velocities of Table X, small circles indicating

the more accurate results obtained from clearly resolved spectra and larger circles the remainder. Measures of the velocities of both components were attempted on four spectrograms within the phase interval 4–10.5 days. Although of low weight, these measures confirm the computed velocity-curve as well as might be expected. The spectroscopic criteria indicate an absolute magnitude of 4.6 for each of the two equal components of the binary.

Carnegie Institution of Washington
Mount Wilson Observatory
May 1931

THE SPECTROHELIOSCOPE AND ITS WORK[1]

PART IV. METHODS OF RECORDING OBSERVATIONS[2]

By GEORGE E. HALE

ABSTRACT

A summary statement of methods of recording observations with the spectrohelioscope and of calibrating the circle of its "line-shifter" is given. A photographic attachment is also described.

Hydrogen flocculi on the sun's disk and prominences at the limb are of two principal types, quiescent and active. The former change slowly in outline and intensity, and as their radial velocities are low, they are best recorded by the spectroheliograph. Active phenomena often appear so suddenly, change so rapidly, and offer such a wide range of radial velocity that they call for the greater flexibility of the spectrohelioscope. This will be appreciated by anyone who has seen the rapid development of an eruption on the disk, and watched the remarkable changes of its intensity and structure revealed by moving the $H\alpha$ line back and forth across the second slit with the line-shifter.

It should be remembered, however, that flocculi which have been quiescent for several days may suddenly develop great velocity, either radial or tangential, with consequent rapid changes in form or position. Possibilities of this kind, which have been described in previous papers, call for special vigilance on the part of observers.

VISUAL OBSERVATIONS

Unfortunately, however, the active phenomena of the solar atmosphere are much more easily seen than adequately recorded. In many cases only a skilled and agile draftsman could hope to depict more than a fraction of the complex series of images, which vary

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 434.

[2] For previous articles in this series see Part I, "History, Instruments, Adjustments, and Methods of Observation," *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, **70**, 265, 1929; Part II, "The Motions of the Hydrogen Flocculi near Sun-Spots," *Mt. Wilson Contr.*, No. 393; *Astrophysical Journal*, **71**, 55, 1930; and Part III, "Solar Eruptions and Their Apparent Terrestrial Effects," *Mt. Wilson Contr.*, No. 425; *Astrophysical Journal*, **73**, 379, 1931.

both with wave-length and with time. Again and again I have been forced to content myself by watching transformations occurring within a few minutes, without being able to obtain a faithful series of drawings. The radial velocities of the various approaching or receding parts, it is true, can instantly be read on the circle of the line-shifter, and with their aid one can determine what is happening. But to put on paper the many successive events, differing for every wave-length, is another matter. It will therefore be understood why in Part II of this series of papers I attempted no more than to record schematically the general changes in character of a few significant flocculi, omitting all others and making no effort to show intricate details of structure.

The fact remains, however, that the most necessary data for similar partial analyses of the flocculi can be obtained by anyone. These data should include (1) the times of sudden changes or other critical events; (2) the approximate heliographic position of the object under observation; (3) the approximate forms of its various parts; (4) the reading of the circle of the line-shifter when each part is shown at maximum intensity, giving its radial velocity at that moment; (5) at least an estimate of the observed maximum intensities, especially in the case of exceptional eruptive phenomena likely to be associated with terrestrial magnetic storms.

1. *Time.*—As a rule, it will suffice to give the time of observations to the nearest minute, expressed in Greenwich Civil Time.

2. *Heliographic position.*—Most of the active flocculi occur near sun-spots, in which case the identification of the spot in question (from the Greenwich publications) will greatly aid in giving the approximate heliographic position. The correct orientation of every drawing, showing the direction of the sun's equator and the true cardinal points, is also needed.[1]

[1] The simplest method of determining the position (heliocentric latitude and longitude) of any point on the sun is with the aid of a set of the Stonyhurst cardboard disks, ruled with meridians and parallels, obtainable at low cost from Casella & Co., Parliament Street, London, S.W. 1. An excellent account of the use of these disks was given by the late Father Cortie in the *Memoirs of the British Astronomical Association*, **23**, Part II, 1921. To meet the needs of the simple telescope used with the spectroheliscope, the disks may be photographed down to the diameter of the solar image, when focused on the first slit through a piece of deep-red glass.

3. *Form.*—Sketches, even if merely schematic, should be drawn to scale. All the spots of the group, as seen on the continuous spectrum beyond the edge of $H\alpha$, should first be quickly sketched with a blue pencil; the most significant parts of the dark flocculi should then be added in black and the more important bright flocculi in red. Several such sketches of active flocculi may be needed for different positions of the line-shifter, followed by other sets of sketches made as the flocculi change in form and radial velocity. A small transparent glass scale,[1] mounted so that it can be turned into position close to the plane of the second slit, may be employed for measuring the areas of flocculi and their distance from spots, but during most of the observations it should be swung out of the way, as it interferes with the perception of the more delicate details.

4. *Radial velocity.*—This is given (with a probable error of 2 or 3 km/sec.) by the circle of the line-shifter, after it has been calibrated by determining the displacement in angstroms of any narrow sharp line near $H\alpha$ corresponding to each interval of 10° on both sides of the zero. For moderate circle readings the relationship will be linear, but a reduction table or curve will be needed to interpret the larger readings.[2]

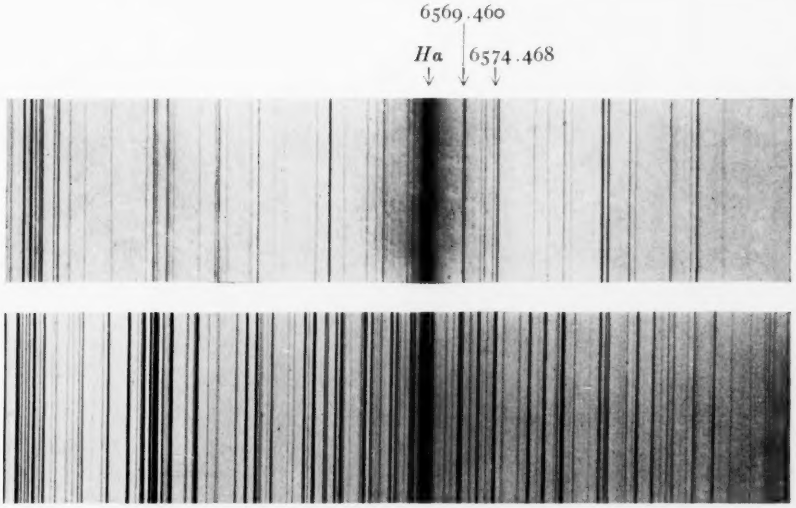
[1] I have used with oscillating slits a linear scale 10 mm long, each millimeter divided into tenths, and a 7-mm square divided into smaller squares, made by the Leitz Co. for microscopes, on thin glass disks 15 mm in diameter. Either can be swung into place beneath the eyepiece, and rotated in position angle. The squares serve for the measurement of the areas of flocculi.

[2] To experienced spectroscopists, provided with wave-length tables and large-scale maps of the solar spectrum, the calibration of the circle will offer no difficulties. In several cases, however, the observers in our long chain of co-operating stations are not thus equipped. It may therefore be a convenience to provide here a photograph of the $H\alpha$ region, with the wave-lengths of the lines used in the calibration of my own instrument and an outline of the process. (Plate X*a*, *b*)

The wide $H\alpha$ line, in the deep red of the solar spectrum, occupies a region where the telluric lines caused by the gases of the earth's atmosphere are both numerous and variable. Their intensity and number change greatly with the altitude of the sun and the state of the atmosphere, so that the spectrum sometimes becomes almost unrecognizable. For determining the scale it is convenient to use two solar lines a short distance from $H\alpha$ toward the red, at wave-lengths 6569.460 and 6574.468. The linear distance between these lines in my spectrohelioscope, using the first order of the grating, is 1.21 mm. As the lines differ in wave-length by almost exactly 5 A, this means that 1 mm equals 4.13 A.

The distance between the lines can be measured with sufficient precision by means

PLATE X

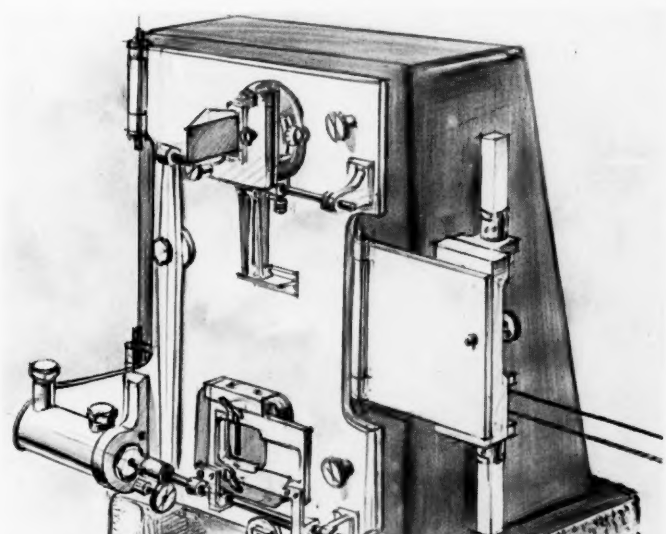


a

b

$H\alpha$ region in solar spectrum: *a*, high sun; *b*, low sun, showing increased number of telluric lines.

c



Attachment for quickly transforming a spectrohelioscope into a spectroheliograph.

The circle reading giving the radial velocity is taken to be that at which the region of the flocculus in question, whether dark or bright, is of maximum intensity. An exception to this rule is occasionally shown by flocculi that exhibit maxima of intensity on both the red and violet sides of the center of $H\alpha$. In such cases the radial velocity may be uncertain. Objects especially calling for measurement are easily distinguished by turning the line-shifter back and forth and noting whether an arched flocculus, for example, shows at one extremity a maximum of intensity only on the red or the violet side of $H\alpha$, which moves toward its other extremity as the line-shifter is rotated.

5. *Intensity.*—For most purposes it will suffice to record the intensity of either bright or dark flocculi on a scale of 3, calling faint objects 1, those of moderate intensity 2, and those either very black or very bright 3. It must be remembered, however, that the intensity is determined by a great number of factors, including among others the nature and condition of the grating and the various optical parts employed, the widths of the first and second slits, and the amplitude of oscillating slits, or the size of the rotating prisms when Anderson's device is employed with fixed slits. Moreover, with a given instrument the apparent intensity of the flocculi

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of the small linear scale divided to tenths of a millimeter mentioned in the last footnote. If the second slit of the spectrohelioscope cannot be opened wide enough to permit both lines to be seen at once, it may be removed altogether for this purpose. The millimeter scale is mounted in or very near the plane of the slit, and the lines and scale are observed with a positive eyepiece magnifying 8 diameters, clamped centrally above the glass scale.

It is assumed that the first slit has been narrowed sufficiently to make the solar lines very narrow and sharp, and that the circle of the line-shifter is set at zero when measuring the distance between them.

To calibrate the circle, turn the grating until the sharp iron line λ 6569.460 falls as close as possible upon the central division of the glass scale when the circle of the line-shifter reads zero. Then make two or more readings of the circle, turning it alternately to right and left, to check the coincidence and determine any necessary correction to the first approximate zero.

Repeat this process for each successive division of the glass scale. We then have a series of measures that will give the displacement in angstroms of a solar line corresponding to any reading of the circle. As a displacement of 1 A at $H\alpha$ corresponds to a radial velocity of 45.7 km/sec., the measurement of the radial motions in the solar atmosphere becomes a very quick and simple operation.

or their parts also depends upon their distance from the center of the sun and the distance of the second slit from the center of $H\alpha$. The condition of the observer's eye is another important factor; the observing room should be as dark as possible, and the direct solar image should not be examined, at least with the same eye, just before looking at the flocculi.

For these and other reasons an exact measurement of intensity is difficult. Probably it could be obtained with the aid of a glass wedge of neutral tint, by comparing the point of extinction of the flocculus with that of a given part of the continuous spectrum not far beyond the wing of the $H\alpha$ line; or some other form of comparative photometer might be better.

When no photometer is used the value of the results will depend chiefly upon the experience of the observer, which will develop rapidly with practice.

PHOTOGRAPHIC RECORDS

The time will come, I hope, when the striking phenomena revealed by the spectrohelioscope in active regions of the solar atmosphere will be fully recorded with a suitable moving-picture attachment. The extremely rapid variations in brightness and velocity which they often exhibit, and the corresponding changes in structure shown by light of different wave-lengths, limit the possible exposures to periods too short for our present photographic plates, in spite of their sensitiveness. With more efficient instruments, giving much brighter spectra of adequate dispersion, I trust these difficulties may ultimately disappear.

Although a skilled draftsman, working rapidly, can sketch the principal phenomena, while one less skilled can at least indicate their general character, even a partial photographic record is desirable. I have accordingly devised an attachment for the standard spectrohelioscope which quickly transforms it into a spectroheliograph. This is similar in design to the moving-prism device used with the combined vertical spectroheliograph and spectrohelioscope in my Solar Laboratory in Pasadena, partially illustrated in Plates XXV, XXVI, and XXVII of the first article of this series.

The purpose of this attachment is not to give a spectroheliograph

capable of photographing the entire solar image or its smaller details, but merely to utilize a certain type of spectrohelioscope for recording on a small scale a few striking and significant flocculi with light of various wave-lengths. The moving right-angle prism is therefore limited in dimensions, and the sensitive plate in the present case is only 1 inch square. With a 2-inch solar image this affords space for two or three successive photographs of the small part of the sun covered by an eruption on the disk. As the scale is so small, the various phenomena corresponding to any setting of the line-shifter are only roughly indicated in relative position, form, and brightness. Such a record will aid the visual observer in fixing the scale of his sketches; but if finer details of structure are desired, a larger solar image is needed, given by a coelostat telescope of larger aperture and more perfect construction than the small one described in my first paper.

Speed in operation is essential, and the apparatus shown in Plate X*c*, from a sketch kindly made by Russell W. Porter, is therefore designed to swing quickly into or out of position. The slit end of the 13-foot spectrohelioscope is assumed to be of the type shown in Plate XIX of my first paper, with fixed slits and Anderson's rotating prism. The rotating prism-support is mounted on pivots, so that it may instantly be turned out of the way when it is to be replaced by the spectroheliograph attachment. Thus when the observer detects some interesting phenomenon, such as an arch showing a wide range of radial velocity, he ascertains visually the two or three positions of the line-shifter that reveal its most characteristic features. He then turns the rotating prism to one side and swings the spectroheliograph attachment into place over the first and second slits. This permits him to photograph a strip of the solar image about a quarter of an inch wide, or large enough to include the region containing the flocculus in question. This exposure, we may assume, is made with the line-shifter set at the best position to show the approaching gases, i.e., so as to bring the necessary wave-length on the violet side of $H\alpha$ upon the second slit. Subsequent exposures may be made with light from the center of the line and then from the point on its red wing where the receding hydrogen is best shown. In practice, a larger number of photographs, corresponding to a greater

number of wave-lengths, may be desirable. But it often happens near active spot-groups that the changes of radial velocity are so sudden that further visual observations are quickly needed to determine a new set of wave-lengths for another series of photographs which should be made without delay.

Mr. Porter's sketch is so clear that little explanation of the apparatus is necessary. The hydraulic cylinder to the left is similar to the clepsydra used to drive my original spectroheliograph at the Kenwood Observatory in 1892.[1] Its piston rod is attached to the end of the lever arm that moves the photographic plate across the fixed second slit, and a weight, hung from the cord at the bottom of the sketch, produces the motion. The upper end of the lever, half as long as the lower, moves the right-angle prism horizontally at half the speed of the plate. Under these circumstances the solar image and plate move at the same speed. The loss of light with this form of spectroheliograph is small, and the excellent contrast obtainable is shown by the series of five photographs reproduced in Plate XXIII*b–f*, in the first paper of this series.

These photographs, made with a precisely similar optical system, represent part of a 3.5-inch solar image given by a 6-inch spherical concave mirror of 30 feet focal length, used with the coelostat telescope of my Solar Laboratory. The parallel rays from the second mirror of this coelostat are sent vertically downward, and the spectroheliograph and spectrohelioscope stand parallel to each other, as illustrated in the paper just mentioned. Thus two observers can work simultaneously, one watching the rapidly changing structure of short-lived phenomena and determining the wave-lengths necessary to record them, while the other makes exposures with the spectroheliograph, which is provided with a line-shifter corresponding to that of the adjoining spectrohelioscope. In this way a greater number of photographs can be obtained in a given time, but even with the standard spectrohelioscope and smaller coelostat telescope, an attachment like that shown in Plate X*c* will enable a single observer to photograph the most significant phases of rapidly chang-

[1] A better hydraulic drive has been designed and will soon be tested. The arrangement shown here, however, will serve fairly well.

ing flocculi sufficiently well to check the accuracy in scale of his sketches and give the relative positions, forms, and brightness of the many details involved.

If all the necessary information regarding the flocculi could be obtained from photographs taken at the center of $H\alpha$, the task of the observer would of course be greatly simplified. This, as we have seen, is not true of the active dark flocculi, which exhibit a great variety of significant changes in velocity and corresponding structure. The bright flocculi, however, usually have a very low velocity of approach, even in the case of the brilliant eruptions on the disk described in the third paper of this series.[1] Although their later stages may be accompanied by dark flocculi characterized by great velocities of approach or recession, the initial bright outburst, which usually seems to mark the critical moment needed in determining the time interval between solar and terrestrial disturbances, as well as the subsequent development of the bright flocculi, may be recorded with the second slit set on the center of the calcium (H or K) or the hydrogen lines.

If one of the calcium lines (preferably K) is used, a single-prism spectroheliograph of only 15 inches focal length will serve to photograph the bright flocculi during the various phases of such eruptions on the disk. A glance at the illustrations in Part III of this series of papers will show the importance of such a series of photographs, even if made with a small solar image and very simple apparatus. The small spectroheliograph I used on Mount Etna in 1894 in some attempts to photograph the solar corona without an eclipse[2] represents the type of instrument I have in mind. This would serve as a useful auxiliary of the spectrohelioscope, especially when bright eruptions are in progress. It would also be easy to modify it for use as an automatic instrument, to take photographs of the sun at regular intervals (say every five minutes) throughout the day for the purpose of recording all bright eruptions on the disk.

A very simple spectroheliograph of the same type, with small

[1] "Solar Eruptions and Their Apparent Terrestrial Effects," *Mt. Wilson Contr.*, No. 425; *Astrophysical Journal*, **73**, 379, 1931.

[2] *Astronomy and Astrophysics*, **13**, 662, 1894.

coelostat telescope, both so designed that they can be made by any boy at trifling expense without the aid of machine tools, has recently been tested at my Solar Laboratory. This will be described, with full structural details, in the *Scientific American* for October, 1931. It was built by my instrument-maker, Mr. Hitchcock, who also constructed the apparatus shown in Plate X*c* and contributed in many ways to its design.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
June 1931

THE TOTAL ABSORPTION OF SOME HYDROGEN LINES IN STELLAR SPECTRA

By C. T. ELVEY and P. C. KEENAN

ABSTRACT

The total absorptions of $H\alpha$ for eighteen stars of spectral types B2 to Ko have been made. For sixteen of the stars the total absorptions of $H\beta$, $H\gamma$, and $H\delta$ have also been determined.

The following observations of the total absorptions of Balmer lines of hydrogen in stellar spectra are those that have been obtained on a rather extensive program which had to be discontinued. The observations are being presented in the hope that they may be of some value to other investigators.

The contours of the $H\alpha$ line were obtained from spectra taken with the three-prism Brashear spectrograph attached to the 12-inch refractor of the Yerkes Observatory. The scale at $H\alpha$ is 54 A per millimeter. Ilford, and Wratten and Wainwright Panchromatic plates were used, each being calibrated with a tube sensitometer through a red filter (Wratten light filter No. 29, F). The plates were developed with Eastman formula D-11. Most of the lines $H\beta$ and $H\gamma$ were published by C. T. Elvey[1] but are collected here along with a few new determinations to make the list more complete. The $H\delta$ lines have been determined from spectrograms made with the single-prism Bruce spectrograph. The scale at $H\delta$ is 20 A per millimeter. The spectra were photographed on Eastman 40 plates and have been calibrated with a tube sensitometer and developed in D-11.

The contours have been reduced by the usual methods from microphotometric tracings, and the total absorptions have been obtained by measuring the area under the curve with a planimeter. The unit of total absorption is 1 A of complete absorption. The values obtained are given in Table I. Those determined from single-prism spectrograms are designated by an asterisk (*). A rather curious appearance was noticed on a single-prism spectrogram of 77 ϵ Ursae Majoris taken on December 15, 1926, where the total absorption of

[1] *Astrophysical Journal*, **71**, 191, 1930.

Hα is nearly four times the value obtained with the three-prism spectrograph. An examination of the plate and of other plates taken on the same night indicate that it is not an instrumental variation. We hardly believe that it is a real change in the star but are recording it in case others may notice similar changes. On the same plate *Hβ* is

TABLE I

TOTAL ABSORPTIONS OF HYDROGEN LINES

Star	Sp.	m_V	*Hα*	*Hβ*	*Hγ*	**Hδ*
67 α Virginis	B2	1.2	2.3	4.4	3.7	4.4
85 η Ursae Majoris	B3	1.9	*5.2	6.6	8.5	6.9
22 ζ Draconis	B5	3.2	3.0	7.4	9.3	6.9
26 β Persei	B8	var.	7.1	7.9	8.9	8.2
32 α Leonis	B8	1.3	*9.2	6.3	9.5	8.8
54 α Pegasi	A0	2.6	9.8	*10.9	*6.9	9.4
3 α Lyrae	A0	0.1	11.8	18.2	21.2	14.9
5 α Coronae Borealis	A0	2.3	8.4	16.6	16.3	14.7
77 ε Ursae Majoris	A0p	1.7	5.8 *(21.9)	11.7	14.7	11.0
65 δ Herculis	A2	3.2	7.1	13.0	13.5	15.8
79 ζ Ursae Majoris (br.)	A2p	2.4	8.9	16.8	21.5	10.4
50 α Cygni	A2p	1.3	0.9	2.8	3.2	2.4
24 α Piscis Australis	A3	1.3	13.9	18.2	18.1	17.9
55 α Ophiuchi	A5	2.1	8.8	*17.6	*21.7	16.2
53 α Aquilae	A5	0.9	5.9	13.7	13.1	9.8
5 α Cephei	A5	2.6	8.4	7.7	13.1	11.1
16 α Bootis	K0	0.2	4.5	1.5	....	....
57 γ Andromedae	K0	2.3	*3.6	....	....	....

* Single-prism.

present; but since the plate is not calibrated for that wave-length and the spectrum is somewhat out of focus, no measurements have been made. However, it has a much widened and diffused appearance, in marked contrast to the usual character of the lines in this star.

An examination of the table shows that *Hα* and *Hδ* are in agreement with the former observations[1] of *Hβ* and *Hγ* in respect to their variation with spectral type.

YERKES OBSERVATORY
August 1931

[1] Elvey, *loc. cit.*